A Technical and Economic Framework for End-to-End Realization of the User-Centric Telecommunication Paradigm

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Abstract

The realization of a user-centric paradigm in future telecommunication networks, which implies free and automatic choice among different available wireless and mobile access networks, will revolutionize the future Internet. For this innovative concept to materialize, a paradigm shift is required from contract-based mobile service delivery to an open, dynamic service delivery environment. This dictates that all stakeholders of telecommunication market (e.g., spectrum holders, network / service providers, and users) will adapt their strategies, objective functions, and decision making mechanisms to cope with the envisioned user-centric telecom landscape. The dynamics of next generation wireless networks will force operators to translate the most commonly used objective functions of throughput maximization, resource utilization, call blocking minimization, etc. into user satisfaction. Ideally providers should be equipped with user satisfaction evaluation / estimation frameworks to attain such objectives, specifically when operators are faced with dynamic spectrum trading (e.g., with spectrum brokers) on one hand and competition for short term contractual users on the other. In such a dynamic telecommunication paradigm, the strategies of all stakeholders are clearly interdependent and achieving any global objective function of user satisfaction depends on the scope of modeling the interactions among all involved stakeholders and their strategies.

The basic emphasis of this thesis is to model the decisions of different stakeholders (i.e., users, providers, and spectrum holders), study their interdependencies, and propose a comprehensive technical framework to realize the user-centric telecommunication paradigm. In this connection, the decision of network selection is modelled at user level, service-offer computations and spectrum-demand estimations are studied at the operator level, and dynamic spectrum allocation problem is addressed at spectrum holder level. Owing to the mobility of users, changing contexts, varying user preferences, and dynamic wireless medium characteristics, the

complexity of system grows and the environment may not be assumed constant. Thus we needed to study and explore the dynamic behavior of such dynamic system that does not only involve the time dependencies and state of environment, but also the variability of demands, uncertainty of system parameters, time delays, error and noise in the measurements over long-term interactions. One way of modeling such dynamic interactions is to introduce learning and adaptive procedures, which we have also done in the thesis.

The thesis covers the following main dimensions: I) Introducing a generic user satisfaction function for Real Time (RT) and Non-Real Time (NRT) applications - The proposed user satisfaction function is based on the utility theory and validated against subjective and objective measurements. It captures the user behavior from both technical and economic perspectives, as well as the technology handover and codec switchover costs. II) Modeling user-centric network selection - Based on the proposed user satisfaction function, user-centric network selection is modeled and an IMS-based realization framework is suggested. The ping-pong effect produced by frequent handovers is also addressed in the framework. III) Operator-centric resource utilization - Concentrating on operators' strategies for attaining the goal of optimal resource utilization and still satisfying the user requirements, a Kalai-Smorodinsky based bargaining solution for resource sharing is proposed, which is then extended to multi-operator scenario. IV) In the future dynamic telecom landscape, network providers will be faced with decisions over dynamic spectrum demands, which also influences their extended service offers to the users, both technically and economically. This forms the basis of our next contribution, i.e., extending the interactions that capture the system-wide dynamics with all stakeholders involved in the end-to-end service provision. We also study the equilibrium characteristics in such interactions. V) In the more complex and dynamic environment of future wireless networks, users and providers have only the numerical values of their utility functions as representative information. This component of the thesis introduces various distributed and heterogeneous reinforcement learning schemes, which are specific to the learning aspects of both payoffs and strategies of the players. We study the system dynamics with different learning schemes in network selection and introduce the novel concept of "cost-to-learn", which is then extended to study the coalition based network selection. We also highlight open research issues in this regard.

Abstract

Die Realisierung eines benutzer-zentrischen Paradigmas in Telekommunikationsnetzwerken, was die freie und automatische Auswahl zwischen verschiedenen verfügbaren drahtlosen und mobilen Zugangsnetzwerken impliziert, wird das zukünftige Internet revolutionieren. Damit sich dieses innovative Konzept durchsetzen kann muss ein Paradigmenwechsel weg von vertragsbasiertem Mobilfunkservice hin zu einer offenen, dynamischen Mobilfunkumgebung. Dazu ist von Nöten, dass alle Teilnehmer am Mobilfunkmarkt (z.B. Lizenznehmer von Mobilfunkfrequenzen, Netzwerk / Service Anbieter und Mobilfunkteilnehmer) ihre Strategien, Zielfunktionen und Entscheidungsmechanismen anpassen, um der vorausgesehenen benutzer-zentrischen Telekommunikations-Landschaft gerecht zu werden. Die dynamische Entwicklung der nächsten Generation drahtloser Netzwerke wird die Mobilfunkanbieter dazu zwingen ihre meist genutzten Zielfunktionen zur Durchsatzmaximierung, Ressourcenauslastung, Minimierung von "Call-Blocking" usw. in Nutzerzufriedenheit zu übersetzen. Idealerweise sollten Anbieter mit einem System zur Evaluierung / Abschätzung der Nutzerzufriedenheit ausgestattet werden, um diese Ziele zu erlangen. Dies gilt insbesondere, wenn die Mobilfunkanbieter mit dynamischem Frequenzhandel (z.B. durch Frequenzbroker) auf der einen Seite, sowie Wettbewerb um Nutzer mit kurzzeitigen Verträgen auf der anderen Seite konfrontiert werden. Mit einer solchen dynamischen Telekommunikations-Umgebung sind die Strategien aller Teilnehmer klar voneinander abhängig und das Erreichen jeglicher. Das Erreichen einer globalen Zielfunktion der Nutzerzufriedenheit hängt somit ab von der Modellierung der Interaktionen aller Teilnehmer und ihrer Strategien.

Der grundliegende Schwerpunkt dieser Doktorarbeit ist es die Entscheidungen der unterschiedlichen Teilnehmer zu modellieren (also der Nutzer, der Mobilfunkanbieter und der Frequenz-Lizenznehmer), ihre Abhängigkeiten zu studieren und ein

umfassendes technisches Framework vorzuschlagen, um das benutzer-zentrische Paradigma in Telekommunikationsnetzwerken zu realisieren. In diesem Zusammenhang wird die Entscheidung der Netzauswahl auf Benutzerebene modelliert, Berechnungen zu Service Angeboten und Abschätzungen des Frequenzbedarfs auf Anbieterebene studiert, und die Problematik der dynamischen Frequenzzuweisung auf der Ebene der Frequenz-Lizenznehmer addressiert. Aufgrund der Mobilität der Nutzer, sich änderndem Kontext, veränderlichen Nutzer-Präferenzen und dem dynamischen Charakter des drahtlosen Mediums wächst die Komplexität des Systems und die Umgebung kann nicht als konstant angenommen werden. Daher war es erforderlich das dynamische Verhalten eines solch dynamischen Systems zu studieren, welches nicht nur die Abhängigkeit von der Zeit und den Zustand der Umgebung involviert, sondern auch die Variabilität der Nachfrage, die Unsicherheit der Systemparameter, zeitliche Verzögerungen, Fehler und Messungenauigkeiten bei langfristigen Interaktionen. Eine Möglichkeit solch dynamische Interaktionen zu modellieren ist die Einführung lernender und adaptiver Prozeduren, was in dieser Arbeit ebenfalls erbracht worden ist.

Die vorliegende Doktorarbeit deckt die folgenden Hauptrichtungen ab: I) Die Einführung einer generischen Nutzer-Zufriedenheitsfunktion für Echtzeit und Nicht-Echtzeit Applikationen - Die vorgeschlagene Nutzer-Zufriedenheitsfunktion basiert auf der Nutzentheorie und wurde in Bezug auf subjektive und objektive Messungen validiert. Sie beinhaltet sowohl das Nutzerverhalten aus technischer und ökonomischer Perspektive, als auch die Kosten für ”technology handover” und ”codec switchover”. II) Modellieren der nutzer-zentrierten Netzauswahl - Basierend auf der vorgeschlagenen Nutzer-Zufriedenheitsfunktion wird die nutzer-zentrierte Netzauswahl modelliert und ein IMS-basiertes System zur Realisierung vorgeschlagen. Der Ping-Pong Effekt, der von häufigen Netzwechseln herrührt wird in dem Framework ebenfalls adressiert. III) Anbieter-zentrische Ressourcen-Nutzung - Bei einem Schwerpunkt auf Anbieterstrategien für das Erreichen einer optimalen Ressourcen-Nutzung mit gleichzeitiger Erfüllung der Benutzeranforderungen, wird eine Kalai-Smorodinsky basierte Verhandlungs-Lösung zum teilen von Ressourcen vorgeschlagen, welche dann erweitert wird zu einem Mehr-Anbieter Szenario. IV) In der zukünftigen dynamischen Telekommunikations-Landschaft werden Netz-Anbieter mit Entscheidungen zur dynamischen Frequenz-Nachfrage konfrontiert werden, was ebenfalls ihre erweiterten Service Angebote gegenüber den Endnutzern beeinflusst, sowohl auf technischer als auch auf ökonomischer Ebene. Dies begründet eine weitere Kontribution dieser Arbeit: Die Erweiterung der Interaktionen, welche das systemweite Kräftespiel aller in der Ende-zu-Ende Service-Beziehung involvierten Teilnehmer erfassen. Weiterhin werden die Gleichgewichtseigenschaften solcher Interaktionen untersucht. V) In der komplexeren und dynamischeren Umgebung der zukünftigen drahtlosen Netzwerke haben Nutzer und Anbieter lediglich die numerischen Werte ihrer Nutzenfunktion als repräsentative Information. Dieser Teil der Doktorarbeit führt verschiedene verteilte und heterogene Schemen zu Verstärkungslernen ein, welche spezifisch für den zu lernenden Aspekt von Payoffs und Strategien der Spieler sind. Es wird die System-Dynamik mit verschiedenen Lern-Schemata bezüglich der Netzauswahl studiert und das neuartige Konzept der "Lernkosten" eingeführt, welches dann erweitert wird um die koalitionsbasierte Netzauswahl zu studieren. In dieser Richtung werden auch offene Forschungsfragen hervorgehoben.

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Erklärung der Urheberschaft

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Berlin, den 10.10.2011 Manzoor Ahmed Khan

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GLOSSARY

3GPP- 3^{rd} Generation Partnership Project
ABC - Always Best Connectivity
AHP - Analytical Hierarchy Process
AMBR - Aggregated Maximum Bit Rate
AP - Access Point
B2BUA- Back-To-Back User Agent
BER - Bit Error Rate
BID - Binding Unique Identification
BUL - Binding Update List
CAC - Call Admission Control
CDF - Cumulative Distribution Function
CoA - Care of Address
CN - Correspondent Node
CRRM- Common Radio Resource Management
CSO - Communication Service Operator
DSA - Dynamic Spectrum Allocation
DSMIPv6- Dual Stack Mobile Internet Protocol version 6
EC- European Commission
ECC- European Communication Commission
EGT- Evolutionary Game Theory
EMA- Exponential Mean Average
EPC- Evolved Packet Core
ePDG - evolved Packet Data Gateway
EPG - Electronic Program Guide
ESS - Evolutionary Stable State
FCC - Federal Communication Commission
FDD - Frequency Division Duplex
FEC - Forward Error Correction
FR - Full Reference
FTP - File Transfer Protocol
GBR - Guaranteed Bit Rate
GRA - Grey Relational Analysis
GRC - Grey Relational Coefficient
GUI - Graphical User Interface
HA - Home Agent
HoA - Home Address
HSDPA - High Speed Downlink Packet Access
HTTP - HyperText Transfer Protocol
IETF - Internet Engineering Task Force
IMS - IP Multimedia Subsystems
IQX - Interdependency of QoE and QoS
KSBS- Kalai-Smorodinsky Bargaining Solution
LTC - Long Term Contractual Agreements
LTE - Long Term Evolution
MBMS- Multimedia Broadcast and Multicast Service Center
MAG - Media Access Gateway
MAP - Mobility Anchor Point
MCoA- Multiple Care of Addresses

MIMO - Multiple Input Multiple Output
MIPv6 - Mobile Internet Protocol version 6
MN - Mobile Node
MNP - Mobile Network Provider
MOS-LQ- Mean Opinion Score-Listening Quality
MOS-CQ- Mean Opinion Score-Conversational Quality
MOS - Mean Opinion Score
MRTD - Multi-Radio Transmission Diversity
MVNO - Mobile Virtual Network Operator
NGMN - Next Generation Mobile Network
NR - No Reference
NRT - Non Real Time
OFDMA- Orthogonal Frequency Division Multiple Access
PDN-GW- Packet Data Network - GateWay
PESQ - Perceptual Evaluation of Speech Quality
PRB - Physical Resource Block
PSQA - Pseudo-Subjective Quality Assessment
PMIPv6- Proxy Mobile IPv6
PRB - Physical Resource Blocks
PSNR- Peak Signal to Noise Ratio
QAM - Quadrature Amplitude Modulation
QCI - Qos Class Identifier
QoE - Quality of Experience
QoS - Quality of Service
RAN - Radio Access Network
RSS - Radio Signal Strength
RT - Real time
RTT - Round Trip Time
RRP - Return Routability Procedure (RRP)
SAE - System Architecture Evolution
SB - Spectrum Broker
SCF - Service Control Function
SDF - Service Discovery Function
SLA- Service Level Agreements
SNR - Signal to Noise Ratio
SPR - Subscription Profile Repository
SSF - Service Selection Function
SSIM - Structural Similarity Index
STC - Short Term Contractual Agreements
UE - User Equipment
UPSF - User Profile Server Function
URI - Uniform Resource Identifier
VoD - Video on Demand
VoIP- Voice over Internet Protocol
VCG - Vickery Clark Groove
WB-PESQ - Wide Band - PESQ
WLAN- Wireless Local Area Network

1

Introduction

"The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York, and it meows in Los Angeles. The wireless is the same, only without the cat." -Albert Einstein

1.1 The Future Wireless Dilemma

As foresightedly and playfully illustrated in Albert Einstein's aphorism, wireless service consumers in future may not need to know what wireless technology, base station, access point or router they are using at a given moment. The growth pattern of wireless, mobile devices, and Internet technologies leads to such revolutionized communication market e.g., almost deployed and yet awaited 4G wireless networks. When it comes to defining the envisioned future wireless networks, we find the diverging and converging opinions of the resource while defining the Buzz words such as *4G*, *ubiquitous*, and *seamless mobility*, etc. However, one may confidently claim that future wireless technologies will exhibit improvements on *throughput maximization*, *improving user perception of services*, *service reliability*, *attempt to ensure communication anywhere and everywhere*, etc. The mentioned expectations from the future wireless networks provision the concept of *large scale convergence* to be realized. In this connection, the advent of multi-interface terminals, advanced heterogeneous technologies integration solutions, flow splitting approaches, service based / interface based flow management solutions, etc. prove to be promising guidelines towards attaining the expected goals and provide clear advantage in terms of coverage, bandwidth utilization, throughput maximization, load balancing, and cost maximization. It can further be observed that given the converged network paradigm and multi-interface terminals shift the problem of simple connectivity to a more sophisticated optimization problem. For instance, the scenario with overlapping radio cells and multi-interface terminals open up the possibilities for selecting appropriate access networks or sharing access networks to ensure that all applications receive preferable QoS, reliability, etc. Thus it will be more appropriate to say that the envisioned 4G aims at providing end-users with an *Always Best Connectivity* (ABC) facility, users' preferred QoS, enough bandwidth resources for future dynamic and bandwidth hungry applications taking user preferences on the service costs into account. It is strongly believed that the ABC concept is highly subjective and is mainly derived from user expectancies over different *technical* and *economic* evaluation parameters. Intuitively, this concept alters the objective functions of different players of the future telecommunication markets.

From users' perspective, the decision problem turns out to be the selection of suitable network(s), whereas the operators will be striving to solve the optimal resource allocation problem and still satisfying the user service demands, meaning thereby operators' objective function turns out to be increasing the satisfied user pool. Accepting the fact that telecommunication market will shift from *network-centricity* paradigm to the *user-centricity* paradigm, operators are faced with dynamic user demands, this dictates that there may be situations when the operators with their statically allocated spectrum resources may be driven into loaded (congested) or under-loaded states. It motivates operators to implement the *Dynamic Spectrum Allocation* (DSA) approaches, where the spectrum can be traded for shorter time periods.

1.2 The Point of Interest

In order to illustrate the point of interest of the thesis, we first briefly discuss the functions of different telecommunication players, we also comment on their positions in the telecommunication landscape. Consider the Fig 1.1, where we define four hierarchical levels namely (from top to bottom); i) Spectrum level, ii) Operator level, iii) Access Network technology level, and iv) User level.

At spectrum level, the scarce spectrum resources are auctioned, thus the decision making problem of the player(s) at this stage is to declare the winner operators, decide over the amount of spectrum to be allocated to the winner bidder(s), and the price that spectrum provider charges for the allocated spectrum resources. As can be seen that the operator level is sandwiched between two levels i.e., spectrum broker level and user level (we neglect here the technology

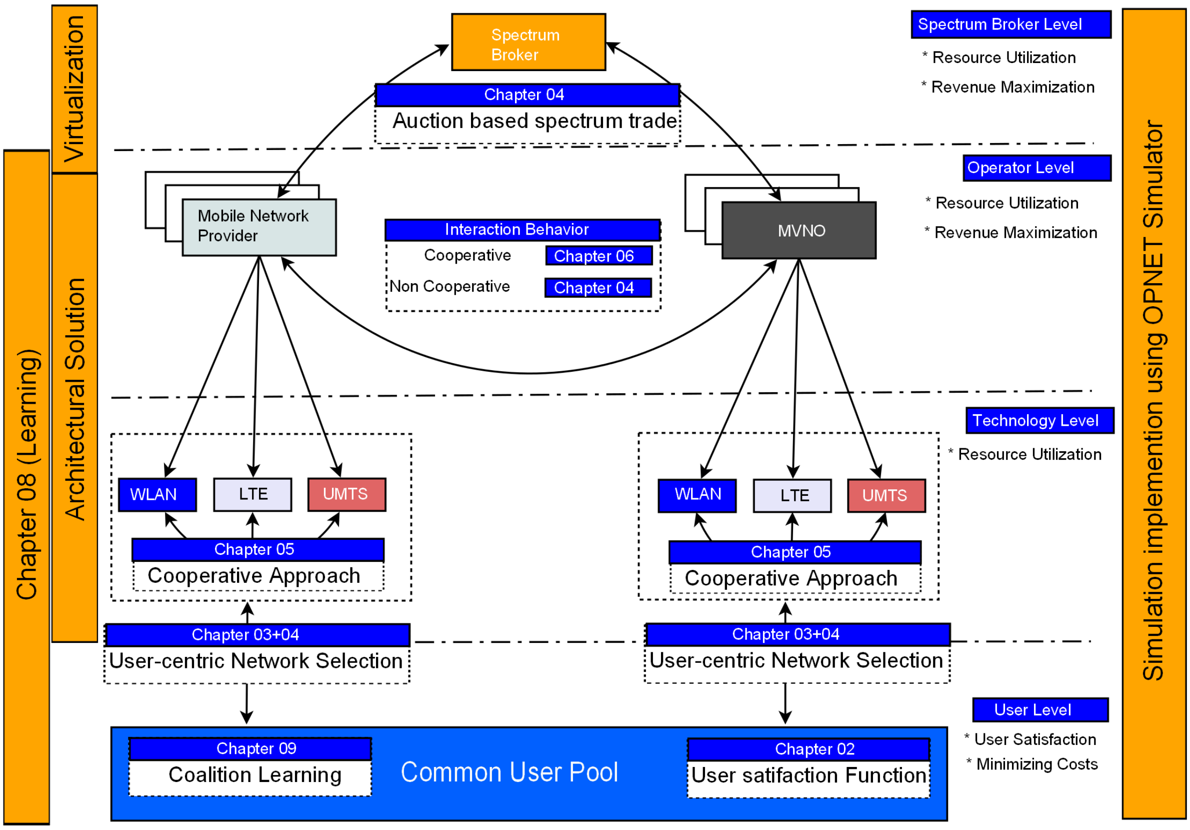

Figure 1.1: Overview of thesis contribution - Figure depicts different hierarchical levels of telecommunication landscape, where the players at each level, the position of each player and their payoffs are defined. On each level, the contributed chapters and approaches used therein are shown. The vertical bars on both sides correspond to the scope of implemented evaluation and proposed technical realization solutions.

level, as we consider it as an implicit part of the operator level). Such position of an operator dictates that there exists minimum two decision instances i.e., one at each interface. Operator's decision for spectrum-operator interface is the amount of spectrum demand and their (private) valuation of the spectrum resources (formulating the bids), whereas operator's decision for user-operator interface is to formulate the service offers to the user i.e., bandwidth allocation, setting service prices, etc.

The solutions at the *network access technology* level can basically be graded as the technical realization solutions. This claim is driven by the fact that at this level, the policies, decisions, or algorithms of operators are realized through technical solutions e.g., solutions focusing on mobility management for seamless connectivity such as MIPv6, PMIPv6, etc., architectural solutions for operators' cooperation, flow management, and network technologies integration, etc. Thus the strategies or objective functions at this level are influenced and implicitly translated into the operators' objective functions.

Having accepted the good news that future wireless paradigm will be user-centric, where users are enabled to control their consumed services according to their preferences over different *technical* and *economic* aspects. This on one hand dictates that user-operator contracts will span over short time quanta, where the operators are expected to offer different network and application level services targeted at improving the overall wireless experience of users, with different service pricing in order to increase revenue by attracting more consumers. On the other hand readers will agree that the handover triggers that simply switch to any better access network as soon as available, could disappoint users with possible frequent connection discontinuities and depending on running applications, would not necessarily improve performance. This also dictates that handover decisions based on the traditional Radio Signal Strength (RSS) comparison remain insufficient. Thus a point can be made here that the decision for selecting the most optimal network may be based on the user preferred application QoS level, preferred bandwidth requirement, residual capacity in each available network, network coverage and cost, etc.

Now that we have presented the general functionalities, positions, and objectives of different players in the telecommunication paradigm, we are in position to discuss their dependency(ies) on each other and relevant issues that are the focus of this work. Consider the Fig 1.2, as can be seen in the figure that when users are delegated with the decision of network selection, they (users) need to evaluate the operator offers at the time of network selection. It is also clear from discussion so far that such decision instance falls under the category of

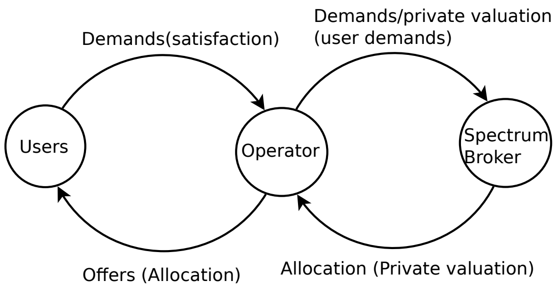

Figure 1.2: Dependency of telecommunication players over one another - Figure represents the functional dependencies of each player over the other. These dependencies are highlighted by the transitional trajectories from state-machine like states (which in this case represent the players) e.g., the transition condition *Demands (satisfaction)* represents the user demands dependency on their satisfaction level, where the user demands are extended to the operators.

multi-criteria decision making. Apparently such decision making is purely subjective. But a common user might not be able to translate the technical QoS indices into her preferences. Similarly knowing the mapping function from QoS to user perception of the QoS, operators may find themselves in a better position to formulate the service offers (which are extended to the users). However, modeling the *user satisfaction*, that exhibits the realistic estimated satisfaction level of the users, is a complex problem, since the user satisfaction is function of both *technical* and *non-technical parameters*. So this expands the QoS $\sim$ QoE mapping problem to a wider spectrum, which can be envisioned as *technical* + *non-technical offers* $\rightarrow$ *user satisfaction function*. Such a user satisfaction function is also useful for online optimization problems from the operators' perspective. Thus there is a need to model satisfaction function.

Now that the above argument establishes a point that *user-centric network selection* depends on the operators' offers. This can be seen (in Fig 1.2) from the demands(satisfaction) transition extending from users to the operators. Given the user satisfaction function, the next step would be to model the *user-centric network selection* decision making. One could clearly indicate two obvious issues here i.e., modeling the network selection and providing the architectural / technically viable solutions that can realize the *user-centric network selection* approach, where user may not initially be associated to any available network operator. Moving up to the operator level, in the user-centric network selection configuration, operators strive to increase their profit by dynamically adapting the service offers and at the same time aiming at optimal resource utilization, balancing the load, etc. These objective functions can be defined on different fronts, when it comes to the load balancing and resource utilization in the network technologies convergence concept, the operators strive to make optimal use of the radio resources within the deployed infrastructure resources. An operator with deployed infrastructure may find potential revenue maximization windows in DSA concepts. However, for this operators need to estimate the amount of spectrum needed in very near future, though the literature may term DSA as real-time spectrum trade, the realistic procedure follows that operators trade the spectrum rights for dynamic time quanta, which may be very small when compared with long-term such that the operators trade for the spectrum to be utilized at time instance (t+1) at time instance t. This dictates that operators should have a fair estimate of spectrum demands, Fig 1.2 shows that this estimation over spectrum demand and valuation of spectrum are directly influenced by the user demands.

At the operator level, operators may cooperate or compete to maximize their objective functions. However, the strategies available to the operators may also be driven by the operator potential / operator types (e.g., MVNO/MNP). Thus the bids formulation at this stage is dependent on the estimated demands and operator competition / cooperation strategies. When it comes to the spectrum broker level, implementing DSA, service broker can introduce efficiency in spectrum utilization, encourage new entrants in the telecommunication market, maximize revenue, etc. Once the operators have acquired the spectrum, they need to sell it to the users, meaning thereby, the price paid for the spectrum and amount of spectrum allocated to the operators influence the operator offers that are extended to the users. This completes the loop-back procedures of telecommunication players, which is depicted in the figure as well. We are convinced that the decision making of all the involved stake-holders need to be modeled to realize the user-centric paradigm aiming at studying the end-to-end system performance in terms of resource utilization, user satisfaction, call blocking, social surplus maximization. We claim that in the envisioned future wireless market, in addition to solving the decision problem at each hierarchical level, the inter-levels players decisions have to be considered. We also claim that with dynamic strategies of all the players in addition to the wireless medium dynamics, the solution should focus on dynamic approaches and distributed approaches. Having explained all the inter-dependencies one may expect that for various decision instances real-time information might not be available or it may turn out to be computationally expensive to collect the relevant information for each cycle of decision instance. This argument further motivates us to claim that introducing learning approaches to decision problem will be attractive research dimensions.

1.3 Contribution

Thesis focuses on modeling the decision instances and interaction of all the involved telecommunication players with explicit focus on modeling the interactions between different players at different layers and solving the decision problems. We also capture the interdependencies of players' strategies over each other in the proposed cross hierarchical layers interaction. Our contribution can broadly be summarized as follows:

- ***User Satisfaction Function*** - The proposals available in the research literature in the direction of *user-centric network selection* either concentrate on the technical indices and neglect other aspects such as economic, user trust, etc. or propose any mathematical function without validating it against subjective or objective measurements. We propose a utility theory based user satisfaction function, that captures user satisfaction for both *technical* and *non-technical* parameters, we also validate the proposed user satisfaction against subjective and objective measurements.

- ***Extended User Satisfaction Function*** - We extend the proposed user satisfaction function by introducing the codec switch-over, handover costs, and cost of learning concepts. These costs play an important role in the network selection specifically in the case of mobile users. To the best of our knowledge, this contribution can be counted amongst the first ones that models the codec switch-over, introduces economic aspects and the costs of learning concept to the user satisfaction function. We also investigate the equilibrium characteristics in presence of all the dynamic parameters such as codec switch-over, handover costs, packet delays, packet loss rate, service prices offerings, etc.

- ***Auction-based Network Selection*** - Network selection algorithms are available in the research literature, but the user's decision of network selection in most of the research literature is either modeled as a static optimization problem or the authors make use of the user satisfaction functions that may not capture the realistic user perception of service (e.g., considering the user's satisfaction w.r.t. technical indices only and not considering the economic aspects) or lack the architectural / technical realization frameworks for their proposed network selection approach. We propose the auction based network-selection approach and make use of our proposed user-satisfaction function. We also address the problem of ping pong effect produced by the frequent handovers using fuzzy logic and MOS (Mean Opinion Score) based solution. The performance of the proposed approach is evaluated against various approaches in terms of user satisfaction and operator objective functions.

- ***IP Multimedia Subsystem (IMS) based Architectural Solution*** - Realizing the proposed network selection approach, the mobility management turns out to be a crucial issue, specifically when it comes to the heterogeneous wireless technologies. We present the realization framework which is based on the IMS and 3^{rd} Generation Partner Project (3GPP) recommendations. In this connection, we study in detail and implement the Proxy Mobile IPv6 (PMIPv6). In order to realize the concept of simultaneous flow management, we also study and implement the Multiple Care of Addresses (MCoA) based solution. We present the interactions and procedures among the involved players on granule level (e.g., SIP messaging formats, sequence of actions etc.). We also implement the simplified architectural solution using OPNET network simulator to investigate the behavior of users and operators.

- ***Network Technology Level Cooperation*** - Concentrating explicitly on operator's objective function, we propose a novel *Kalai-Smorodinsky bargaining* based network centric technology level cooperative approach. Owing to the novelty of the used approach in this direction, a publication based on this contribution was awarded the *Best Paper Award*. We model the resource allocation problem as a bankruptcy problem and solve the conflict using bargaining solution. The solution is based on flow splitting and simultaneous use of interfaces on cooperative resource sharing. In order to realize the proposed flow splitting based resource utilization approach. We make use of the MCoA based flow management approach. We also extensively implement such flow management using network simulator (the details may be found in the Appendix).

- ***Operator Level Cooperation*** - We extend the cooperative network technology level approach on the similar lines to the operator level. However, in this configuration, we introduce a trusted third party i.e., Service Level Agreements (SLA) broker which acts as the Common Radio Resource Management (CRRM) entity at the inter-operator level. We highlight the gain of the cooperation in multi-operator scenarios with different configurations. The interaction in this modeling basically involves the *technology-operator* and *operator-operator* interaction using *cooperative game theoretic* approach.

- ***Modeling operators' competition for Spectrum and Users*** - At the operator level, we also model the operators' competition for the amount of spectrum from spectrum provider in the DSA configuration. For such interaction, we consider the operators of different potentials, where the potential can be taken as the operator strength (with respect to its available resources, etc.) in the communication market. We model the competitive behavior of the operators and investigate the equilibrium characteristics within this interaction. In order to differentiate the operators on the grounds of incurring costs, we detail the cost components of both the types of operator and capture the cost components in the proposed interaction modeling.

- ***Modeling Estimated Spectrum Demands and Operators' Private Valuation*** - At the operator level to address the issue of estimating the spectrum demands in competitive and DSA enabled environment, we model the user service request demand using *Mean Square* and *Exponential Mean Average* (EMA) methods. We also discuss the generic algorithm to compute estimated demands of two different types of operators in the user-centric paradigm. We implement the EMA approach for estimating the demands in the implemented OPNET simulator.

- ***Modeling the interaction among different wireless communication players*** - We capture the behavior of all the players positioned at different levels in the modeled cross level interaction. We make use of the proposed user satisfaction function, model user network selection using game-theoretic approach and propose the interaction *spectrum broker-operators* using uniform price auctioning theory. We investigate the equilibrium characteristics for different strategies of the involved players.

- ***Learning in Network Selection*** - Having accepted that the future wireless network will exhibit a lot more dynamic and uncertain behavior argument, where users and operators have only numerical values of their payoffs as information. We construct various heterogeneous combined fully distributed payoff and strategy re-enforced learning. We investigate the game dynamics and learning schemes in the network selection in heterogeneous wireless networks and introduce the novel approach *cost-to-learn*. The performance of the proposed game-theoretic learning approaches have been analyzed by applying it to the user-centric IPTV service selection approaches.

- ***User Coalition Formation in Network Selection*** - Given the user-centric network selection scenario, operators with the view to increasing their user pool, may offer different incentives to the users to motivate them form coalitions. We present novel approach of coalition network selection. The interaction is modeled using Evalutionary game theory approach. We examine the global optima in the coalitional network selection configuration. The performance of the approach is analyzed by the OPNET based simulation within the considered configurations.

- ***Proof of Concept*** - To present the proof of concepts of all the proposed models, we rely on *objective* and *subjective* measurements in addition to the analytical proofs. We extensively implement the *flow management* using MCoA, RFC 5648. We implemented various filter rules for flow splitting specifically to realize the network-centric resource utilization approach. However, we use the flow splitting implementation in realizing the user-centric approach. For the purpose of objective measurement, we created impairment entity, setup the simulation setup with heterogeneous technologies for validating user satisfaction for different application types i.e., audio, video, and data applications. For the validation of user satisfaction for video applications, we also integrated a third party evaluation tool in our simulation steup. We also used testbed for validating subjectively the switchover and handover cost component of the proposed utility function. We implemented the proposed architectural solutions using OPNET simulator to evaluate the performance of various proposed solutions. We also used the virtualization framework of LTE for realizing the proposed spectrum market.

1.4 Thesis Organization

We pictorially represent the organization of thesis in Fig 1.1. The placement of chapters on different levels in the figure shows that the chapters contribute on that level. It should be noted that multiple appearances of chapter name on different levels indicate that the chapter contribution cover multiple levels. We categorize the chapter under three major categories namely i) user-centric network selection category, ii) operator-centric resource allocation, and iii) learning in user-centric network selection. We now briefly summarize each category and the chapters therein.

1.4.1 User-Centric Network Selection Category

This category mainly focuses on the addressing the issues related to user-centric network selection paradigm. We start with modeling the realistic user-satisfaction function, then modeling the auction based user-centric network selection decision problem. This category also presents the architectural solution for realizing the proposed network selection approach. In the end, we capture the full length interaction among all players in the user-centric network selection paradigm, where we investigated the system efficiency at different levels. Furthermore, approaches like DSA, competitive *operator-operator*, competitive *user-operator*, and *spectrum broker-operators* approaches are proposed and their performance evaluated. This category also discusses the learning aspects in the cross hierarchical levels interaction approach. The category is basically decomposed into following three chapters.

1.4.1.1 Chapter 02: User Satisfaction Function

In this chapter, we model the user satisfaction function using utility theory. The proposed satisfaction function (user utility function) is then validated against the objective measurements (i.e., OPNET simulation based measurements) for different service types including *audio*,*video*, and *data*. We also categorize the users into three different user types namely i) excellent, ii) good, and iii) fair user types. The user satisfaction model is then extended to capture the codec switchover and handover costs for both mobile and static users. The extended user utility function is validated against the subjective test results. We also introduce the *cost of learning* approach to the user utility function and investigate the equilibrium characteristics.

1.4.1.2 Chapter 03: User-Centric Network Selection

This chapter focuses on studying the user-centric network selection models. We model the user-centric network selection using *auction theory* approach. The contributed user-centric network selection model is based on the user utility function proposed in Chapter 02. We also discuss in detail the IMS based architecture and inter-entities SIP based interactions that realizes the proposed user-centric network selection model. We then investigate the performance of the proposed approach against various approaches in terms of *call blocking*, *resource utilization*, *handover costs*, and *service costs*, etc.

1.4.1.3 Chapter 04: Multi-tier Resource Allocation and Network Selection

This chapter involves the decision instances of more stake-holders (telecommunication players) when compared with Chapter 03. In this chapter, we model the profit functions of all the involved stake-holders followed by modeling the interaction among them. This chapter somehow summarizes the concept of user-centric network selection in a bigger picture i.e., the model captures the interdependencies of different stake-holders over each other and the impact of such inter-dependencies over the profit / gain of each player. We also discuss the equilibrium characteristics and simulate. LTE virtualization is proposed as the realization framework for the proposed spectrum broker procedures.

1.4.2 Operator-Centric Resource Allocation Category

In this category, we deviate from the basic question of *user-centricity* and concentrate on *operator-centricity* by focusing on the efficiency in the network resource allocation by network operators. We model the resource management in multi-operator scenario and study the efficiency of the proposed model in different settings. The motivation behind studying the operator-centric resource allocation comes from the following facts:

- Current communication market is *operator-centric*, where the objective of the network provider is driven by the efficiency in resource utilization, which can further be translated into operators' revenue. Thus a rational operator strive to maximize its revenue. It should be noted that most of the research literature in this direction can in general be grouped under the title of *throughput optimization problems* and such solutions do not specifically take into account the user satisfaction (QoE) for the extended services.

- One of the telecommunication business model dimensions is that operators may form a joint venture and such decisions may be time and space specific. Thus in such case, the resource sharing approaches should be investigated for the efficiency.

- Having attained the results for network centric resource allocation, we will be in position to compare the performance of proposed *operator-centric* and *user-centric* approaches. However, in such a case scenarios have to be made comparable.

This category basically comprises of the following three chapters:

1.4.2.1 Chapter 05: Operator-Centric Resource Allocation - Single Operator Perspective

This chapter focuses on the resource allocation within the single operator scenario, where the model for resource sharing based on cooperative game-theoretic approach is proposed. The performance of the proposed approach is analyzed in terms of resource utilization, call blocking rate, and compared against the earlier approaches available in the research literature.

1.4.2.2 Chapter 06: Operator-Centric Resource Allocation - Multiple Operator Perspective

This chapter extends the proposed model of the single operator resource allocation approach to the multi-operator scenario. Interaction among different players (operators and network technologies) is modeled at two hierarchical levels. The resource utilization efficiency is analyzed for all the involved operators.

1.4.2.3 Chapter 07: Performance Evaluation of Operator-centric against User-centric Approach

This chapter studies the operators' gain in *user-centric* and *operator-centric* settings. This study basically investigates the behavior of operators' gain in the proposed user-centric and operator-centric network selection approaches.

1.4.3 Learning in Network Selection Category

This category introduces the concept of learning to the network selection problem discussed in the earlier chapters. We focus on investigating the game dynamics and learning schemes in network selection. In this category, we discuss the coalition formation at the user level using evolutionary game theoretic approach. We also highlight the open research issues, when it comes to the use of coalitional game theoretic approaches. This category is decomposed into following two chapters:

1.4.3.1 Chapter 08: Learning in Network Selection

In this chapter, we study game dynamics and learning schemes for network selection in heterogeneous wireless networks and introduce a novel learning scheme called *cost-to-learn*. We construct various heterogeneous combined fully distributed payoff and strategy reinforcement learning. We study the performance of the proposed learning approach by applying it to a user-centric wireless network scenario and user-centric IPTV service provider selection scenario. The proposed concept was appreciated and awarded with the best paper award.

1.4.3.2 Chapter 09: Coalition Based User-Centric Network Selection

In this chapter, we focus on the user coalition formation in the user-centric paradigm, we present a novel approach of coalition network selection. We use evolutionary game-theoretic approach to model this problem. We also examine fully distributed algorithms for global optima in network selection games. Then, the problem of dynamic network formation and evolutionary coalitional games in network selection are investigated. The performance of the proposed approach is studied through simulations using OPNET modeler 15.0.

1.5 Publications

In the following, we mention few selected book chapters, journal, and conference papers which resulted as the outcome of this thesis. The contents of the published contributions are modified to construct the thesis chapters. It should be noted that most of the thesis work is peer reviewed and published i.e., (MK1) (**Best paper award**),(MK2),(MK3), (MK4) (**Best paper award**),(MK5),(MK6),(MK7),(MK8),(MK9),(MK10),(MK11),(MK12), (MK13), (MK14).

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Part I

User Centric Network Selection Category

This category focuses on discussing the user-centric network selection approaches. We model the user satisfaction function using utility theory approach, which is then used in the proposed network selection model. After we have modeled the user satisfaction function and network selection, we extend problem scenario to a more realistic one by including more telecommunication stake-holders (i.e., spectrum broker in addition to the Network provider, Mobile Virtual Network Operator, etc.). This category is decomposed into following three chapters:

- **Chapter 2** *User Satisfaction Function* : In this chapter, we model the user satisfaction function using utility theory. The proposed satisfaction function (utility function) is then validated against the objective measurements (i.e., OPNET simulation based measurements) for different service types including *audio*,*video*, and *data*. We also categorize the users into three different user types namely i) excellent, ii) good, and iii) fair user types. The user satisfaction model is then extended to capture the codec switchover and handover costs for both mobile and static users. The extended user utility function is validated against the subjective test results. We also introduce the *cost of learning* approach to the user utility function and investigate the equilibrium characteristics.

- **Chapter 3** *User-Centric Network Selection* : This chapter focuses on studying the user-centric network selection models. We model the user-centric network selection using *auction theory* approach. The contributed user-centric network selection model is based on the user utility function proposed in Chapter 2. We also discuss in detail the IMS based architecture and inter-entities SIP based interactions that realizes the proposed user-centric network selection model. We then investigate the performance of the proposed approach against various approaches in terms of *call blocking*, *resource utilization*, *handover costs*, and *service costs*, etc.

- **Chapter 4** *Multi-tier Resource Allocation and Network Selection* : This chapter involves more stake-holders when compared with Chapter 3. In this chapter, we model the profit functions of all the involved stake-holders followed by modeling the interaction among them. This chapter somehow summarizes the concept of user-centric network selection in a bigger picture i.e., the model captures the inter-dependencies of different stake holders over each other and the impact of such inter-dependencies over the profit of each stake-holder. We also discuss the equilibrium characteristics and simulate. LTE virtualization is proposed as the realization framework for the proposed spectrum broker procedures.

In Table 1.1, we present the notations used in this category and the description for these notations.

Table 1.1: Notations and their description

Notation	Description
$u_{j,k,c}(o,n)$	Utility function of user j when associated with operator o
k	Index of service type
θ	Finite set of user types
c	Index representing the service class (e.g., audio, video, etc.)
$\overline{u}_{j,o}$	Maximum utility in lossless condition (bandwidth dependent utility of users)
β_c	The sensitivity of application c towards the amount of received bandwidth
co	Index of codec
w	Index of network technology
$\tilde{u}_k^c$	Maximum user satisfaction level for user (service) type k
$\tilde{\pi}_k^c$	Private valuation of user type k
σ	Measures the rate of decay of users' satisfaction
s_o	Index of operator offered security level
ψ	Codec switchover costs
L	Set of considered dependent parameters
L'	Set of considered independent parameters
$\mathcal{K}$	The aggregated cost values
π	The price user pays against the consumed services
ζ	Sensitivity of attribute to traffic class and user profile
$n_{o,k,c,co,w}$	Number of users with (k, c, co, w) associated to operator o
b	Bandwidth
pl	Packet loss
$\tilde{\zeta}$	*Handover* costs
$\tilde{r}_o$	Index of operator reputation
φ	*Codec-switchover* costs
$\nu_{j,c}$	Current valuation of user j / gain component of user j
$\nu_{j,e}$	Estimated valuation of user j
$\mathcal{S}_o$	Strategy space of network operator o
$\mathcal{S}_j$	Strategy space of user j
V	Current revenue.
ci_o	Incurring cost by operator o
$R_{o,e}$	Expected revenue of operator
$\phi_i(\tilde{\nu})$	Payoff vector in Shapely solution

Notation	Description
$Q_k^c(l)$	Ideal value of considered *dependent* associated attribute l
ϵ	Price sensitivity of user
d	index representing the delay attribute
$\hat{R}$	Telecommunication landscape (Region)
$\hat{a}$	Index representing the communication coverage area
a_t	Action profile at time slot t
$Cr(\tilde{\nu})$	Core of game with characteristic function $\tilde{\nu}$
$\tilde{\nu}$	Characteristic function
Di	Distance to be traversed between APs
$\tilde{\alpha}$	Relative weight index
Γ	Strategic game
$C_{s,h}$	Aggregated estimated handover and switchover costs
$\mathcal{N}$	Finite number of users
$\mathcal{O}$	Finite number of operators
$\mathcal{C}$	Application set
$r_{k,c,i}$	User request of service c of type k
$a_{k,c,i}$	Allocation of operator resources to user for type k
$\mu_{c,k}$	Maximum achievable user gain in (lossless environment) ideal environment
$b_{k,c}$	Offered bandwidth to users of type k for service c
λ	Tie braking variable
$\tilde{\lambda}$	Decision variable
α	Cost slopes
F^{ss}	Social surplus function
$a^*_{k,c}$	Optimal resource allocation
$\pi^*_{k,c}$	Optimal price
$\tilde{d}$	Disagreement point
t	Time instance
F	Feasible set
$\phi(\tilde{\nu})$	Payoff vector, which is function of $\tilde{\nu}$
C_r	Index of Shapely core
$\tilde{R}$	Auctioneer request vector

2

User Satisfaction Function

One may quote countless instances in real life where the decision is based on multiple evaluating attributes. These attributes may be referred as service performance or service quality measures that provide basis for evaluating various decision(s). When it comes to decision(s) making in telecommunications, quality has a strong positive connotation when it is used in a seemingly neutral context. This dictates that upon introducing some Quality of Service (QoS) improvement procedures to a network, one may assume that service consumer(s) will be more satisfied with the extended service. However, realistically speaking, improvements in QoS can not necessarily be translated in proportional improvements in the user perceived Quality of Experience (QoE). The internet, enhanced communication, and evolutionary network technologies have been entrenched into the current telecommunication era. These advancements on one hand exhibit tremendous impact on the social fabric and on the other hand they shift the focus of service quality evaluation from technical indices to more subjective evaluation criteria involving the user perception. This argument places the user QoE on higher level than technical mechanism when categorizing them with respect to their importance for decision(s) making (specifically network selection decision making) in future telecommunication paradigm.

Given the mentioned facts, there is a need to model the user QoE, which we term as "User Satisfaction Function" hereafter. In this chapter, we propose a utility theory based user satisfaction function, validate the proposed utility function against subjective and objective measurements, introduce the novel cost of learning concept, and discuss the equilibrium characteristics for network selection in the presence of various evaluation attributes.

2.1 Introduction

Next generation wireless networks together with smart phone evolution have opened new opportunities to deliver mobile services to the users. The realization of user-centric paradigm in future heterogeneous wireless networks will revolutionize future wireless networks. For this innovative concept to materialize, a paradigm shift is required from long-term contractual based service delivery to a short term contractual and dynamic service delivery. This poses the challenge of intelligent network selection based on users QoE. Thus the envisioned user-centric paradigm and future business model redefine the operators' objective function and ties it to increasing the numbers of satisfied users. This in turn dictates that it is imperative for operators to estimate the user satisfaction for their extended services. Existing approaches such as *subjective* and *objective* measurements serve the purpose of providing such information to the operators. Good that we have solutions but one could only wish for a solution with no associated issues. These solutions are not recommended for online optimization for various reasons detailed later in this chapter. Analytical model representing the user satisfaction for different services seem good solution that does not only address the issue of computational complexity, but also proves to be a suitable solution for online optimization. In this chapter, we propose user utility function to capture users' satisfaction (QoE). With the view to validating the proposed utility function, we compare the behavior of the proposed utility function to the quality metric curves attained from the subjective and objective measurements. In this connection standard QoE measurement techniques are used to obtain the related quality metric values of services e.g., VoIP service is evaluated using Mean Opinion Score (MOS) values from ITU's E-model; video streaming service by Peak Signal to Noise Ratio (PSNR), Structural Similarity Index (SSIM), and subjective MOS values and FTP service is evaluated using TCP's goodput values. To carry out the *objective* measurements, we use OPNET modeler 15.0 and we also integrate additional simulation tools to our simulator setup a testbed to investigate the QoE for video streaming. While modeling the user satisfaction, one can not ignore the impact of handover costs and codec switchover costs, thus to capture these effects in the proposed utility function, we extend the utility function by including the parameters representing handover and codec switchover costs. We also introduce the notion of *costs of learning* and show that the resultant utility with *cost of learning* is equivalent to the initial utility of users that does not only take into consideration the network QoS related indices and non-technical parameters (price, etc.) of the operators but also the cost of codec changes and network handovers. We compare our theoretical model for extended utility function against the *subjective* measurements. Our results show that the quality prediction by our model has correlation of $r = 0.923$ with subjective testing.

2.2 Related Work and Motivation

In future wireless networks, users will be interested in timely and complete delivery of the data irrespective of the heterogeneous characteristics of underlying network technologies. This dictates that for different applications, the network technologies have to meet certain QoS requirements e.g., real-time applications should expose short response times, streaming applications must meet the requirements of continuity, and streaming large amounts of data requires efficient downloading to minimize the waiting time (7). Applications' quality assessment has been the subject of many researchers, when it comes to speech quality assessment, various models and their modifications have been proposed for signal based speech quality prediction model such as Perceptual Evaluation of Speech Quality (PESQ) and Wide Band (WB)-PESQ (8)(9). Similarly many efforts have been made in parametric based model such as ITU-T E-model (10) and its various extensions. In the context of speech quality assessment when network handovers and codec switchover are prevalent, a comprehensive quality assessment study has been carried out by Möller et al. (11), which encompasses the changes in the user quality of experience for various different roaming scenarios. Their study highlight the fact that packet loss is the most dominant factor in NGMN conditions and network handover (only) has minimal impact compared to packet loss and codec switching. Another interesting fact from that study reveals that when packet loss is high, changing codecs does not impact quality much. However, when the packet loss is low, changing codec has high impact on the quality.

In another recent study by Mehmood et al. (12) authors show that WB-PESQ model failed to predict quality under some NGMN conditions. It was shown with experimental evidence that WB-PESQ underestimates quality due to (i) wideband-narrowband speech codec switching, (ii) speech signal fading during codec switching, and (iii) talk-spurt internal time-shifting due to jitter buffer instabilities. This highlights the fact that current signal based models are still not tuned for NGMN typical conditions and needs enhancement. Similar studies of NGMN conditions carried by Blazej et.al. (13) pointed out that the parametric model such as E-model was unable to predict the quality where narrowband and wideband codecs are present in a single call. Their suggested codec-switching impairment factor to E-model improved the correlation of the E-model prediction to auditory tests to $r = 0.937$. Chen et.al. (14) have tried to find out user satisfaction index of VoIP user, however their work is limited to Skype user satisfaction only. When it comes to the video quality assessment, there are multiple objective video quality measurements available ranging from simple PSNR and average packet loss, to more sophisticated methods of spatially and temporally comparing the decoded video content with a reference signal, more on video quality assessment may be found in (15), (16), and (17).

Correlating the QoS and QoE has also been studied in the research literature, Khirman et. al. in their paper (18) investigated the relation between objective measurements and human perception of the service. The authors focus on studying the user satisfaction for HyperText Transfer Protocol (HTTP) service and the impact of delivery speed and latency on user satisfaction. Similarly (19) proposes a sigmoid function like QoS $\sim$ QoE relation taking into account various QoS parameters for different application types. The authors in (20) base their QoS $\sim$ QoE relationship on the IQX hypothesis (exponential interdependency of quality of experience and quality of service). Authors also review the common reference models and concentrate on loss, jitter, and re-ordering; users ratings as function of response time for web applications through their proposed QoS $\sim$ QoE model. For the relevant literature on QoE, readers my refer to (21) (22) (23). Given the discussion so far, we confidently stand by the following arguments, which also serve to be the motivating force for the work in this chapter. On one hand the rigid fact is that subjective testing approaches are time consuming and incur great costs, on the other hand the alternative objective testing techniques for instance; PESQ, modified E-Model, and Transmission Control Protocol (TCP) goodput, etc. may not be an attractive solutions for online optimization in real-time scenarios. Analytical functions predicting the estimated user satisfaction are candidate solutions to the mentioned issues. Although a few solutions discussed in the research literature make an attempt to address the mentioned issues, but in a limited scenario for limited number of parameters or for limited application types. To the best of author's knowledge, none of the references (in the research literature review) model the user satisfaction considering both technical and non-technical parameters on more granule level and greater scope. By non-technical parameters, we mean the parameters that are not directly technology related, but have impact of user satisfaction, for instance, service costs, operators' reputation, etc. Neglecting such parameters in modeling user satisfaction function obviously lead to false estimation of user satisfaction. However, the degree of deviation from the actual user satisfaction is influenced by the user preferences over different parameters. We, in our model propose three different types of users namely; i) excellent, ii) good, and iii) fair users (the motivation to categorize users in the mentioned three categories will be discussed later in this chapter). We propose a generalized user satisfaction model based on both technical and non-technical parameters. The proposed satisfaction function is scalable to capture the user satisfaction behavior for different service and user types.

2.3 Background

In this section, we briefly discuss the background knowledge needed as prerequisite knowledge for this chapter.

2.3.1 Quality of Service (QoS)

QoS is a broad term and is most commonly used as performance measurement criteria for network systems, as it defines the network perspective of performance. It measures the incidence of errors within network system in terms of *delay, jitter, packet loss, etc.* Measuring the QoS, network systems are enabled to identify and minimize the error indices by; i) enforcing performance measures, such as setting *traffic priorities*, *QoS aware scheduling*, etc., ii) resource over provisioning, etc. In order to ensure that application QoS requirements are met, the operators use standardized measurement tools and techniques to collect the QoS information at different measurement points within the network system. We very briefly comment on a few of such tools and techniques as follows:

2.3.1.1 QoS Measurement Techniques and Tools

Network traffic is used as the basic measurement tool that measures the performance of links' characteristics, and network systems (24). Traffic information at different network points (routers, nodes, etc.) are collected using various QoS measurement tools such as *network analyzers (tcpdump, windump, packetizer, ethereal, etc.).* Traffic information is then analyzed to calculate the performance of QoS metric (24). QoS measurement is objective measurement, where we can achieve concrete quantitative values for the considered performance metric.

2.3.2 Quality of Experience (QoE)

The term QoE as opposed to the QoS defines the users' perspective of service performance. It is the measure of an *ene-to-end performance* level and serves as an indicator of *how well the* *system meets the user preferences.* Fig 2.1 illustrates the basic difference between QoE and QoS. QoE represents the users behavior towards the service she (user) is consuming and is

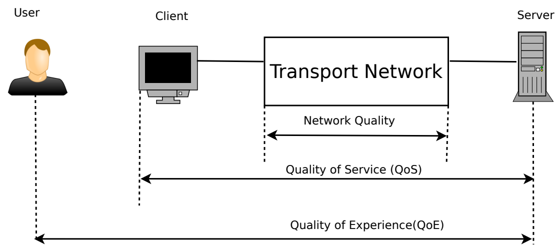


Figure 2.1: QoE and QoS - Figure presenting the difference between QoE and QoS (24)

normally captured through *subjective testing*[1]. Although comparatively more accurate when compared with other measurement methods, *subjective measurement* methods are time consuming, involve exhaustive processing, costly, difficult to be carried out for all the environments, exhaustive to measure for dynamically varying services from time to time, and are not suitable to be used for online system optimization.

An alternate solution that addresses mentioned problems and still predict the estimated user satisfaction for any service is *mapping QoS over QoE* i.e., translating user satisfaction in terms of system technical indices. We justify the need for *QoS over QoE mapping* approach by answering the following basic questions.

1. *Why is QoS $\sim$ QoE mapping needed?*

   In future wireless networks, where the users have short-term contractual agreements with operators, or service providers, the objective of network providers, service providers, and service developers will be driven by the *satisfied user pool*. Attaining this objective the mentioned stake-holders will be interested in knowing the user behavior towards services in different contexts, and such information can only be made available if user satisfaction is mapped over providers' technical indices. Moreover QoS $\sim$ QoE mapping help providers to take performance improvement measures by controlling network parameters (network providers), or develop services keeping the user satisfaction intact (service providers / developers), etc.

[1] Subjective testing involves a panel of humans users, who test the extended service in a purpose built environment (testbed, test room, etc.) and grade the service.

QoE $\sim$ QoE help reduces the churning rate [1], this argument is strengthen by the statistical data presented in (25), where it says that, 82% of customers churning do it due to frustration over the product or service, 90% of customers do not complain before churning, 1 frustrated customer tells 13 others about the bad experience, for each that calls with a problem, 29 never call. Therefore, a supplier cannot rely on customer feedback in order to correct mistakes, as it will probably be too late. Thus, user test data before going to market and good user experience after purchase is critical for customer retention and having a good image for gaining new customers.

2. *What performance metric attributes are needed to represent the user satisfaction and how to find out meaningful mapping functions with objective QoS metrics ?*

   QoS $\sim$ QoE mapping depends on various parameters i.e., mapping function should translate impact of each QoS performance metric into user satisfaction function. This reveals the need for a *universal user satisfaction* metric, which should be the function of QoS performance metric parameters for different applications. It should also be noticed that the QoS measurement metric varies for different applications. For *real-time applications*, most widely used user satisfaction metric is MOS, whereas *non-real-time* applications are generally evaluated in terms of *throughput*.

2.3.3 QoE Performance Evaluation Metrics

1. Mean Opinion Score (MOS): MOS is typically used for real-time applications e.g., audio, and video applications. It is determined from the subjective measurement[2]. Normally when a common service consumer assesses and grades a service based on his perception, she may define her experience of the service as *excellent*, *good*, *fair*, *bad*, and *poor* service. These levels of user perception when expressed numerically is called *quality score*. The *quality score* is numerical number scaled between $[0 - 5]$. The average of *quality scores* assigned by the subjects (users) to a service score is then known as MOS value. The description of specific numerical value in terms of *user satisfaction* is given in the Table 2.1. The translation of QoS into MOS values vary for different applications, discussed in the later sections.

2. Data throughput: Data throughput measures the performance of datarate at access networks

[1]Churning rate is the percentage of subscribers to a service that discontinue their subscription to that service in a given time period.

[2]In subjective measurements real users asses the quality of an application and rate it accordingly.

Table 2.1: MOS Values

Perceived Quality	MOS
Excellent	5
Good	4
Fair	3
Poor	2
Bad	1

for *non-real-time applications*, it refers to the amount of successful *data delivery* over time within a specific digital setup. It is calculated by dividing the amount of *data transferred* by the *time* it takes to transfer the data. This includes packet headers, acknowledgements that packets have been received, and retransmitted data. Throughput is measured in bits per second, or in data packets per second.

3. Goodput: Goodput is related to *throughput* and is calculated by dividing the *original data* by the transfer time.

2.3.4 Utility Function - a brief overview

The term utility comes from the field of economics. Utility is an abstract concept and is derived largely from Von Neumann and Morgenstern (26). It is designed to measure the user satisfaction. A utility function measures users relative preference for different levels of decision metric attribute values. Thus preference relation can be defined by the function, say $U : X \rightarrow \mathbb{R}$, that represents the preference for all x and $y \in X$, if and only if $U(x) \geq U(y)$. Here the concept of Marginal utility is worth mentioning, that represents the additional satisfaction, or amount of utility, gained from each extra unit of attribute. This concept is basic to demand theory which states that marginal utility diminishes as the consumption of an item increases. Basically a utility function should satisfy following properties; i) *non-station property:* let $u(\sigma_i)$ represent the utility function for attribute i, from the attribute space $\Sigma = \sigma_1, \ldots, \sigma_m$, then non-station property states that utility $u(\sigma_i)$ increases with attribute value (given that attribute value is normalized as the greater the better) i.e., $u(\sigma_i) > 0$ and ii) *risk-aversion:* this property states that utility function is concave meaning thereby marginal utility decreases with increasing value of attribute (provided that attribute value is normalized as the greater the better) i.e., $u''(\sigma_i) < 0$.

2.4 Proposed Satisfaction Function

Before we model the user satisfaction using the utility theory approach, we highlight few basic facts that may serve to be the foundation for modeling the users' satisfaction. We start with the basic fact that user satisfaction depends on various parameters (as detailed earlier also). This fact dictates that user satisfaction function should involve most of (if not all) the user satisfaction related parameters, but one can not neglect the fact that capturing the satisfaction for all the parameters turns out to be a complex problem specifically if the user satisfaction function is used for the network selection. The details about network selection decision may be found in Chapter 3, such a decision making comes under the category of multi-criteria decision making process. The multi-criteria decision making process handles multiple criteria in network evaluation function to select the best available network. We now detail the the basic requirements of the user satisfaction function as under:

1. The function should combine all the criteria into one measure that evaluates the networks.

2. Importance of each involved criteria in decision making may be reflected by assigning it weight values.

3. The characteristic of each involved parameter should be realistically captured i.e., for some criteria, a non-linear mapping of values to their quality should be possible.

4. In case of dependent criteria, a criterion must be able to fully affect the network selection decision e.g., if a network provides 60% packet loss for VoIP application and at the same time proves to be ideal for rest of the criteria, this may result in ranking the network as the target network (candidate network) but selecting this network in no way is an acceptable decision. Therefore, utility associated to packet loss must affect the overall decision of network selection. However, here the concept of *dependency* and *independence* should be taken into account. Intuitively, the term *dependency* of one parameter over the other dictates that dependent criteria influence each other to the great extent, and normally their correlation can be obtained by taking their weighted product. The need to use the weighted product approach is justified and strengthen by the requirement $\#4$. i.e, any criteria resulting in $zero$ utility reduces the user satisfaction to $zero$.

5. In case of independent criteria, a criterion should not fully affect the network selection decision e.g., If the reputation of the operator is considered as a network selection or

user satisfaction criterion, then for a new entrant in the market, this criterion will result in always $zero$, although it may offer better services than many other competitors in the market. Normally the correlation of such independent criteria is normally captured by the weighted sum approach. In this case the total utility is $zero$ only if the utility of all the involved criteria result in $zero$.

Remark 1. *The additive sum criteria performs better in aggregation (owing to neutral element as zero), where poor values of criterion has least influence on the satisfaction, and good values improve the evaluation results. On the other hand multiplicative aggregation performs oppositive to good and bad values in evaluation owing to its neutral entity as* 1.

We now specify more concrete the potentially considerable parameters to be considered in modeling the user satisfaction function (more on such parameters is illustrated in Table 3.1 of Chapter 3.)

1. Network conditions: Network related parameters such as traffic, available bandwidth, network latency, and congestion affect the user satisfaction. characteristics, path loss, inter-channel interference, Signal to Noise Ratio (SNR), and Bit Error Rate (BER).

2. Application type: Different types of services such as voice, data, and multi-media applications require different levels of data rate, network latency, reliability, and security.

3. Battery power: Battery power plays an important role in the network selection or handover decisions. Owing to the fact that wireless devices operator on limited battery power. The obvious consequence of considering this parameter in network selection is preferring less power consuming interfaces in situations where power conservation is preferred.

4. Security: It may be defined as the network immunity to various virus and intruder attacks and ensuring the confidentiality of the network. When it comes to the wireless networks, the wireless medium itself turns out to be one of the weakest point in terms of security. Therefore, considering this parameter influences the network selection decision specifying when the information is of confidential nature. Thus users prefer the networks with higher encryption.

5. Cost of service: The cost of services offered is a major consideration to users since different network operators and service providers may employ different billing plans and

strategies that may affect the user's choice of access network and consequently handoff decision.

An important aspect yet to consider is that characteristics of each involved criteria should be normalized, as different involved parameters are most likely measured with different units. The normalization of the criteria values may span between the interval [0,1] or another value range of interest e.g., MOS value [0,5], etc. We now illustrate briefly on the scaling requirements as follows:

1. The scaled value should represent all the possible values of the represented criterion i.e., it should be defined for all the possible values.
2. The scaling values have to be in the defined interval of the criterion.
3. The maximum value of the scaling range has to the upper bound of the interval.
4. The minimum value of the scaling range has to be lower bound of the interval.

It should be considered that attaining the normalized values that represent the user satisfaction for the considered criterion does not conclude utility modeling. As every involved criterion behaves differently and such behavior may be represented by a mathematical function, thus modeling satisfaction function further provisions defining functions to represent the behavior of each involved parameter. The functions may take different shapes i.e., monotonically increasing, monotonically decreasing, linear, step, concave, sigmoid, and coub douglas function, etc. The choice of any of these function is strictly driven by the criterion under consideration and its selection is a crucial issue. Furthermore *fairness* needs to be ensured when scaling the functions among the scaled context parameters used in the evaluation. However, fairness in this context does not mean that all scaled parameters should have the same distribution within the scaled range. This also implies that a compensation among the parameters is possible if they are equally important (e.g., data vs cost per time equally weighted, a doubled data rate is supposed to compensate double costs per time). This means if the overall evaluation should behave the same for two or more criteria, those criteria must use the same characteristic scaling function. If the behavior should be inverse for two criteria, inverse scaling functions are to be chosen. Few of the general scaling functions for generic network selection criteria are shown in Table 2.2

Table 2.2: Functions representing the criteria behavior

Criterion	Description
Delay	monotonically decreasing
Packet loss	monotonically decreasing
Bandwidth	step function / monotonically increasing
Reputation	monotonically increasing
Security	monotonically increasing

From the discussion so far one may categorize the parameters that affect the user satisfaction into two major categories namely i) dependent parameters - the parameters that fully affect the user satisfaction and ii) independent parameters - the parameters that have additive effect over the user satisfaction. Later in this chapter, we will provide and illustrate the definitions of *dependent* and *independent* parameters more concretely and specific to the user satisfaction function for network selection problems.

Note: We use the *user satisfaction function* and the *user utility function* interchangeably throughout this work. This is so done because we use *utility theory* to model user satisfaction function and at times we find it more convenient to use *utility function* instead *satisfaction function*. Thus readers should not confuse, both these terms indicate one and the same function.

Now that we know the basic requirements of utility function, we present the proposed utility function. Let $u_{j,k,c}(o,n)$ represents the satisfaction function of user j when associated with operator o, the proposed satisfaction function takes care of all the mentioned requirements, and is given by:

$$\begin{aligned} u_{j,k,c}(o,n) := \bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right) \prod_{l \in L} (\nu_{jl,o}(k,c,n))^{w_{jl}} - \pi(o,k,c) \\ + \sum_{l' \in L'} \omega_{l'} v_{jl',o}(k,c,n,\psi), \end{aligned} \tag{2.1}$$

We decompose the user utility function into four components:

- The term $\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$ is the function of network state $n = (n^c_{o,k})_{o,k,c}$ and the offered bandwidth $b^c_{o,k}$ by the operator o. The collection n is the vector that represent the total number of users those request the service of specific class.

Table 2.3: Utility control parameter values for VoIP and FTP applications (3)

QCI	Guarantee	Priority	Delay budget	Loss rate	Application
1	GBR	2	100ms	1e-2	VoIP
2	GBR	4	150ms	1e-3	Video call
7	NGBR	6	300ms	1e-6	E-mail
9	NGBR	9	300ms	1e-6	FTP

- $\prod\limits_{l \in L} (\nu_{jl,o}(k,c,n))^{w_{jl}}$ is the weighted multiplicative approach for *dependent* associated QoE attributes.
- $\sum\limits_{l' \in L'} \omega_{l'} v_{jl',o}(k,c,n,\psi)$ is the weighted sum of different *independent* QoE attributes.
- $\pi(o,k,c)$ is the service price offered by operator o to the user type k for service class c.

The first two multiplicative terms take into account both the congestion level of the operator and expected QoE, which is translated from the Operators QoS indices. The weight values w are dictated by the sensitivity of user type, service class to the attribute l' or l. We consider three different service classes namely; i) audio, ii) video, and iii) data service classes.

Here $k \in \Theta$, where Θ is the finite set of user types. Inspired by the concept of Non-Guaranteed and Guaranteed Bit Rate (N/GBR) rate users of LTE, we propose three different types of users namely *excellent*, *good*, and *fair* users. It should be noted that generally GBR or real-time applications have higher priorities than those of Non-GBR or non-real-time applications as advocated by the Table 2.3. However, in reality there are situations when users may set higher priorities to their e-mails than to their video streaming applications, on the similar lines some users may become very annoyed after waiting a dozen of seconds for a web-page to be loaded or refreshed or a user is irritated when waiting all the day long for a video to be downloaded. Thus in such situations it is more realistic to model the utility function based on irritation level of different user types. This dictates that each user is then defined by the irritation level (which in turn can be translated into service quality). The proposed user-types are differentiated by their preference profiles such that an excellent user of service class c prefers service quality most, a fair user prefers less service costs, whereas the good users stand midway.

Our choice of four components for the proposed utility function is deriven by the objective of modeling a generic and rich user satisfaction function. Using the proposed utility function and plugging in the function for any considered parameter, one can obtain the estimated user satisfaction value. However, care should be taken in defining the function and assigning values to the controlling parameters when evaluating user satisfaction for different types of applications.

2.4.0.1 Bandwidth Dependent Utility Component

Availability of bandwidth / transmission data rate plays the key role in evaluating the user QoE, therefore most of the literature work focuses on the impact of varying datarate / bandwidth over QoE. However the user satisfaction should be analyzed with respect to different technical and non-technical attributes, and QoE evaluation metrics vary with respect to application used by the user. We capture the bandwidth dependent user satisfaction with the following utility function components:

$$\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right) := \begin{cases} 0 & \text{if } \frac{b^c_{o,k}}{n_{o,k}} \leq \underline{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}})\frac{1-e^{-\beta(b^c_{o,k}-\underline{b}^c_{o,k})}}{1-e^{-\beta(\overline{b}^c_{o,k}-\underline{b}^c_{o,k})}} & \text{if } \underline{b}^c_{o,k} \leq \frac{b^c_{o,k}}{n_{o,k}} \leq \overline{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}})\frac{1-e^{-\beta(b^c_{o,k}-\overline{b}^c_{o,k})}}{1-e^{-\beta(\tilde{b}^c_{o,k}-\overline{b}^c_{o,k})}} & \text{if } \overline{b}^c_{o,k} \leq \frac{b^c_{o,k}}{n_{o,k}} \leq \tilde{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}})\frac{1-e^{-\beta(b^c_{o,k}-\tilde{b}^c_{o,k})}}{1-e^{-\beta(\widehat{b}^c_{o,k}-\tilde{b}^c_{o,k})}} & \text{if } \tilde{b}^c_{o,k} \leq \frac{b^c_{o,k}}{n_{o,k}} \leq \widehat{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}}) & \text{if } \frac{b^c_{o,k}}{n_{o,k}} \geq \widehat{b}^c_{o,k} \end{cases} \tag{2.2}$$

where $\mu_k(\frac{b^c_{o,k}}{n_{o,k}})$, represent the maximum utility of user types k in the lossless medium and $n_{o,k} = \sum_{c \in C} n^c_{o,k}$ is the number of users of type k for application quality of service class c from the operator o. In order to capture the congestion level, we choose the function μ_k as strictly decreasing function in the number of users that request services at the same operator. The number $b^c_{o,k}$ represents the offered bandwidth to user type k for application quality of service class c, similarly $\underline{b}^c_{o,k}$, $\overline{b}^c_{o,k}$, etc. represents the minimum and maximum required bandwidth by the application quality of service class c and user type k. β_c represents sensitivity of application c towards the amount of received bandwidth e.g., $\beta_{real-time-application}$ $> \beta_{non-real-time-applications}$. The value of β is scaled between the value range $[0, 1]$. For different k type users, $\overline{b}_{excellent} > \overline{b}_{good} > \overline{b}_{fair}$ and $\mu_{excellent} > \mu_{good} > \mu_{fair}$.

Reaction of Bandwidth Dependent Utility Function Towards Real-Time(RT) Applications: *Streaming* and *Conversational* traffic classes can be combined RT applications, which are commonly termed as inelastic or rigid applications. These can further be divided into symmetric and asymmetric RT applications. The concept of symmetric and asymmetric is driven by the amount of resource consumption i.e., in symmetric applications resource consumption at both source and destination is somewhat similar. Examples of RT symmetric applications include teleconferencing, Video-phony and VoIP. Whereas in asymmetric applications requests are less resource consuming than responses e.g., Video and audio broadcasting, Interactive audio / video on demand, etc. Generally RT application are constrained by minimum amount of bandwidth i.e., application is admitted only when the demand for minimum required bandwidth is met. Such stringent requirement on bandwidth are represented by step function, which means that as soon as demand for application required bandwidth is met users maximum utility is reached, and for a slight reduction in this bandwidth below the minimum required bandwidth users utility is $zero$. When it comes to network selection paradigm, triggering the network selection decision is not a good practice. To avoid this we assume that, a small transition region exists between two states of users(fully satisfied, unsatisfied) as shown in Fig 2.2. This assumption is strengthen by the $60 - 80Kbps$ demand of Audio broadcasting, $1.2Mbps - 1.5Mbps$ demand of Video broadcasting with MPEG1 coding standard. These are RT applications, and the ranges represent the transition region. The length of this region is tuned by β, such that the higher the value of β is the smaller is the region. These range bounds are depicted by the range, say $[\underline{b}_k^q - \overline{b}_k^q]$ in Equation 2.2. User types can be defined in this range, since this transition region is expected to be small in case of real-time applications, therefore in such a case the concept of user types is captured by the overall utility function given in Equation 2.1. Our proposed utility function satisfies the call admission control requirement of real time applications.

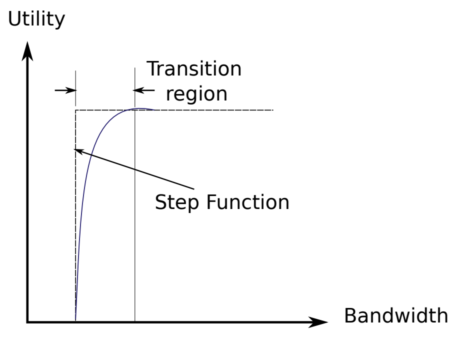


Figure 2.2: Improvement over step function by introducing transition region - Figure highlights the narrow transition region between fully satisfied and fully unsatisfied user states for RT applications

Reaction of Bandwidth Dependent Utility Functions Towards Non-Real-Time (NRT)

Applications:

Interactive and *Background* traffic classes can be combined NRT applications, which are commonly termed as *elastic* applications. As detailed in the previous paragraph these applications are also further divided into symmetric and asymmetric NRT applications. Examples of NRT symmetric applications include Internet relay chat, and NRT asymmetric applications include FTP, Telnet, E-mail, browsing, etc. Generally NRT applications do not have stringent requirements for bandwidth and delay. Such applications can run even with a minimal amount of available bandwidth, therefore call admission control may not be needed in this case. The proposed utility function captures user satisfaction for such applications. The bandwidth requirements by different NRT applications dictate that the utility function is concave, also clear from shanker utility curve (27) e.g., bandwidth requirements for web browsing, E-mail and Telnet are $< 30.5kbps$, $< 10kbps$ and $< 1kbps$ respectively. For NRT application the transition region is bigger and user types are defined over this region, where μ sets the maximum utility of different user types.

2.4.1 Associated *Dependent* Attributes Utility Component

The term *dependent* is driven by the bandwidth dependency on the associated attribute[1], these attribute generally include *delay*, *jitter*, and *packet loss* values. This utility component can also be treated as an implicit bandwidth shaping function. As these associated attributes can be normalized in expectancy *the lower the better*, therefore, we propose the following function to represents user utility for *dependent* associated attributes.

$$\nu_{jl,o}(Q_k^c) := \begin{cases} \mu_k^c & \text{if } Q_k^c(l) \leq \overline{Q}_k^c(l) \\ \mu_k^c e^{(Q_k^c(l) - \overline{Q}_k^c(l))\zeta_k^c(l)} & \text{if } Q_k^c(l) \geq \overline{Q}_k^c(l) \end{cases} \tag{2.3}$$

Here $\nu_{jl,o}(Q_k^c)$ represents the utility of k-type user j for any associated parameter indexed by l. $\overline{Q}_k^c(l)$ represents the *ideal* or *preferred* value of attribute. μ_k^c sets the maximum satisfaction of k-type user, value of $\zeta(l)$ defines the sensitivity of attribute to traffic class and user profile.

2.4.2 Associated *Independent* Attributes Utility Component

The term *independent* here refers to the attributes' independence over the bandwidth i.e., change in the value of the independent associated attribute causes no change on the user received bandwidth. This component of user utility may be the function of various attributes like

[1]Associated attribute = considered parameter for the evaluation of networks

reputation of operator, *security*, *battery life*, etc. These attributes are of diverse scope and can be normalized on expectancies of *the lower the better*, *the higher the better*, or *the nominal the better*. User satisfaction for this component is purely attribute dependent i.e., the decision of using linear, exponential, logarithmic functions and control parameters depend on the attribute under consideration e.g., for security parameter, a function like bandwidth dependent utility may be used.

2.4.3 Price-based Utility Component

In addition to technical parameters, non-technical / economic parameters play an important role in user satisfaction e.g., relatively degraded service may be acceptable to a user with lower price, whereas a user paying higher prices gets irritated immediately with even a minor degradation in the service. This argument strengthens the fact that representation of user QoE without taking economic parameters into consideration is incomplete, therefore we capture users behavior to such parameters by suggesting the price based utility as under:

$$u_{j,k}(\pi_k^c) := \mu_k^c - \frac{\mu_k^c}{1 - e^{\tilde{\pi}_k^c}} e^{-\tilde{\pi}_k^c \epsilon}, \tag{2.4}$$

μ_k^c represents the maximum satisfaction level of user type k, and $\tilde{\pi}_k^c$ is the private valuation of service by user, and ϵ represents the price sensitivity of user.

2.5 Objective Measurements and Utility Function Validation for RT and NRT Applications

This section focuses on validating the proposed user satisfaction function by carrying out the objective measurements for both RT and NRT applications. The section explicitly details the simulation setup that is developed for validating the user satisfaction for each application type.

2.5.1 RT VoIP Applications

As discussed earlier that RT applications have stringent QoS requirements, thus in order to validate the proposed user satisfaction for estimating the user satisfaction for RT applications, we choose VoIP application for the subjective measurements. We now present a brief overview of the standard VoIP measurement followed by the implemented simulation setup and validation results.

2.5.1.1 Subjective VoIP Quality Measurement Overview

Voice subjective tests are based on MOS values. There are two classes of MOS values for voice applications namely, *listening quality (MOS-LQ)*, and *conversational quality (MOS-CQ)*. MOS-LQ is most widely used in VoIP industry. It measures the quality of audio for listening purposes only, and does not take into account the bidirectional effects, such as delay and echo (28). Despite more realistic test environment with MOS-CQ, they are less preferred due to high time consumptions. As stated in section 2.3.3, in subjective measurements, human listeners are asked to rate the service numerically in the range $0 \sim 5$ (refer Table 2.1). Multiple test phrases are recorded and then test subjects listen to them in different conditions. These tests are performed in special rooms with background noises and other environment factors are kept under control for test execution. The test conditions are given in [ITU-T-P.800]. In telecommunications, the most commonly used assessment methods are those standardized and recommended by ITU-T, and include the i) Absolute Category Rating, ii) Degradation Category Rating, and iii) Comparison Category Rating. Readers are encouraged to refer (29) for more details of subjective and objective measurements.

2.5.1.2 Objective VoIP Service Measurement

In such measurements no human listeners are involved, instead an algorithm is used to compute the expected MOS value by observing a speech sample (29). The target of objective MOS measure is to predict the MOS value that is very close to the one attained from the subjective measurement, in other words the objective is to have increased correlation between the two (subjective and objective measures). Voice objective quality measures can further be divided into:

1. *Full reference* - This approach has access to and makes use of the original reference signal for a comparison. It compares each sample of reference signal (talker side) to each corresponding sample of the degraded signal (listener side), such a measurement is based on the computation of distortion between original and degraded speech. PESQ is an example of such algorithms.

2. *No reference* - Such measurement use only the degraded signal and have no access to the original one. NR algorithms (e.g., P.563) are low accuracy estimates, only, as the originating voice characteristics (e.g., male or female talker, background noise, non-voice) of

the source reference is completely unknown. A common variant of NR algorithms do not even analyze the decoded audio signal but work on an analysis of the digital bit stream on an IP packet level only. The measurement is consequently limited to a transport stream analysis.

Examples of FR and NR Measurement Models

- *Perceptual Evaluation of Speech Quality (PESQ ITU P.862)* - PESQ is full-reference algorithm and analyzes the speech signal sample-by-sample after a temporal alignment of corresponding excerpts of reference and test signal. It compares the original / reference voice signal with distorted / received voice signal. PESQ can be applied to provide an end-to-end (E2E) quality assessment for a network, or characterize individual network components.

- *Modified E-Model* - It combines transport metrics e.g., packet delay, delay variation, de-jitter buffer operation, packet loss, frame size, etc. to characterize an error mask (e.g., frame loss rate along with measurement of burstiness). The characterized error mask along with error concealment algorithm and lookup tables for subjective testing produces E-model equipment impairment factor. This equipment impairment factor can then be combined with E-model measurable elements like echo, delay, etc. to predict final MOS value.

We carry out a lengthy round of simulation runs in different scenarios i.e., when users are associated to different codecs using ITU-T PESQ, and modified E-models. In this connection we set up a simulation environment as detailed below.

A primer on Evaluation of VoIP Call Quality in OPNET: As ITU has specified several recommendations for voice quality evaluation e.g., E-model (it was bacially developed for circuit switched network), modified E-model. The E-Model assesses combined effects of variations in several parameters that affect conversation quality of handset telephony. It produces the result called *Rating Factor (R)*, where $R = R_o - I_s - I_d - I_e + A$. R_o is the basic SNR, I_s represents voice signal impairments, I_d represents impairments caused by delay, I_e is equipment related impairments, and A represents the advantage factor. R can be mapped to MOS value. It should be noted that I_s is independent of packet transports. Choosing default value of I_s as 5.8, and setting $R_o = 100$ results in $R = 94.2 - I_d - I_e + A$. OPNET provides several choices for values of R_o, I_s and A. It should be noted that I_d represents the impairment caused by one way ear-to-mouth delay. G.107 provides a table of I_d values of the delay impairment for selected, one-way delay values. For ease of use the following curve fitting function is used $I_d = 0.024d + 0.11(d - 177.3)H(d - 177.3)$, where $H(x)$ is Heavyside function and d is one way packet delay. In IP networks d has the following components; i) codec delay - Encoding delay, look ahead delay, etc. This value is given in codec specification. ii) Packetization delay - if more than one frames are transported in one IP packet. iii) De-jitter buffer delay - in case of out of order deliveries or packet loss, packet waits in de-jitter buffer up to maximum de-jitter buffer length value. iv) Compressing and de-compressing delay - processing delays associated with compression / decompression of voice packets. v) Network delay - Delay experienced by a packet from the time it leaves L7 at source node till it enters L7 at the destination node.

The value of I_e factor is obtained from subjective measurements of voice quality of various codecs and various operating conditions e.g., Packet loss, packet size, etc. Different packet loss concealment algorithms also affect I_e values, ITU-T G.113 Appendix I, (10/2001) specifies I_e factor values as a table for G.711, G.729a, GSM-EFR and G.723a codecs. Based on the given information, curve fitting function of the following form is proposed. $I_e \sim \gamma_1 + \gamma_2 ln(1 + \gamma_3^* e)$, where e is packet loss rate and γ are codec specific constraints. Packet loss rate e has the following components; i) Packet loss rate in the network - All packet losses on the way from source node to destination node due to e.g., link impairments, buffer overflows in transport network routers, etc. ii) De-Jitter buffer packet loss rate - A packet is dropped if it gets delayed more than de-jitter buffer length. R-factor in turn is mapped over the MOS such that for $0 < R < 100$, $MOS = 1 + 0.035R + R(R - 60)(100 - R)7^*10^{-6}$, for $R > 100$ MOS = 100, and for $R < 0$ MOS = 1. ***OPNET Simulation Settings -*** The components involved in

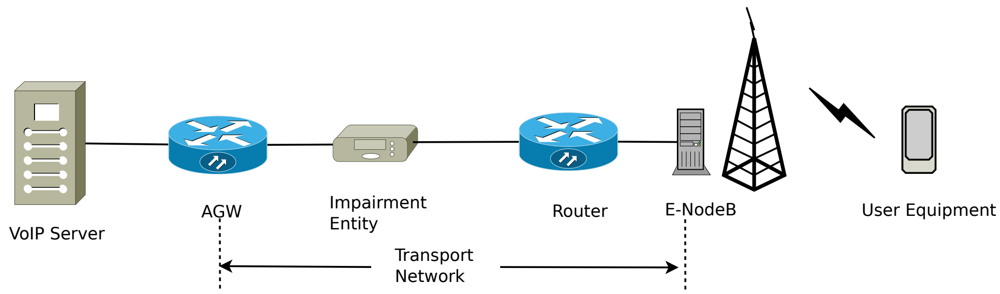


Figure 2.3: VoIP Simulation setup - The figure depicts the architectural setup that is implemented to carry out the objective measurements for RT VoIP applications. We implemented impairment entity, which is used to introduce customized impairments in the transport network, thus providing us with a more controlled measurement environment.

the simulations include; i) Impairment entity - This entity introduces specified packet delay, packet loss and can also limit bandwidth available to a voice communication by performing bandwidth shaping using token bucket algorithm. ii) LTE radio access network, iii) WLAN radio access network, and iv) Transport network. Fig 2.3 illustrates the simulation setup, where the impairment entity resides between the caller and the callee. Impairment entity introduces various delays and packet losses during the lifetime of a VoIP call, we then analyze the user satisfaction for the VoIP call using modified E-Model and PESQ for different values of delay and packet loss.

Remark 2. *The packet delay values in the simulation include only codec delay and transport network delay excluding fixed delay components e.g., equipment related delays, compression decompression delays and other internetwork codec related delays, etc.*

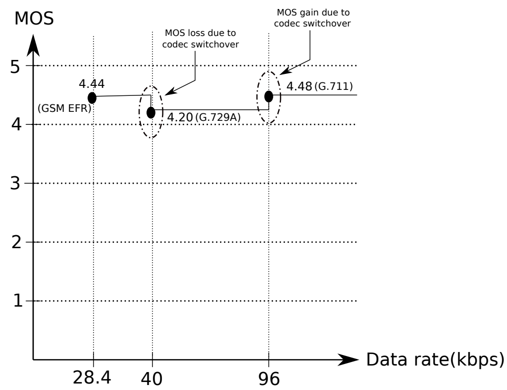


Figure 2.4: VoIP MOS for Loss-less Scenario: - This figure illustrates that MOS values for different codecs in lossless scenario are different i.e., as can be seen that the maximum achievable MOS value for GSM EFR is 4.44, which is different from the maximum achievable MOS value of G.729A. This difference is driven by the different compression and de-compression rates, resulting bitrates, and overhead for packet headers, etc. e.g., G.711 uses a logarithmic compression achieving compression ratio of 1:2 and in G.729 codec the compression rate is 1/8.

Simulation Results - We obtain the simulation results showing the user satisfaction in different scenarios, where users are associated to three different codecs namely; i) G.711, ii) GSM EFR, and iii) G.729. These codecs are characterized by the codec data-rates. Each codec in a lossless[1] condition achieves the maximum MOS, $\overline{MOS}_{co}$, such that $\overline{MOS}_{co} \neq \overline{MOS}_{\overline{co}}$. This characteristic of codec dictates user associated with a codec c, will have lossless MOS

[1]Lossless condition can be defined as an ideal scenario, where packet-loss and delay values are ideally zero.

equal to $\overline{MOS}_{co}$ unless she is switched-over to the codec $\tilde{co}$. Codec switchover results in step-function like $\overline{MOS}$ value[1] of user in a lossless scenario, this is depicted in Fig 2.4. Fig 2.4 clearly shows that even in a lossless scenario, codec switchover introduces a marginal gain or loss in the MOS value.

We now discuss a more realistic scenario, where user satisfaction is influenced by the packet loss and delay values i.e., user associated with a specific codec co, with the MOS, $\overline{MOS}_{co}$, experiences delay and packet loss in the communication system. The consequence of system impairments is a degraded service, which in turn has negative impact on user satisfaction. In simulations, we use *impairment entity* to introduce customized delays and packet losses in the system and study the impact of parameter values on *user satisfaction*. Fig 2.5 shows the impact of delay and packet loss values on user satisfaction for $G.711$, $G.729$, and GSM EFR codecs, As can be seen that all the codecs lead to different MOS values for different values of packet loss and delays.

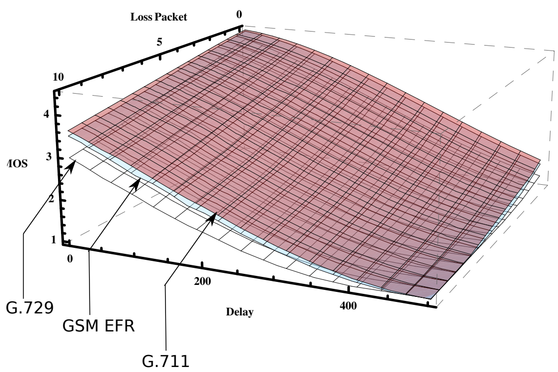


Figure 2.5: MOS values for different codecs: - The figure shows MOS values for different packet loss and delay values for three different codecs i.e., GSM, EFR, and G.729. One can observe that G.711 performs better than the other codecs. This is due the various differences amongst these codecs e.g., G.729 uses approximately 20Kbps for upstream downstream, thus G.729 provides good call quality while minimizing bandwidth usage. One noticeable difference between G.711 and G.729 arise during on-net calls, where G.711 offers a higher quality on-net call because G.711 does not compress audio, when it comes to G.729, it is compressed but still sounds good (as can be seen from the curves in figure). Its really a trade off between bandwidth and call quality. In general somewhat similar behavior as that presented in Fig 2.4 is now presented continuously for different values of packet loss and delay values.

[1]We can also translate the decrease or increase in MOS value, by the user satisfaction loss and gain respectively.

Table 2.4: Utility control parameter values for VoIP, FTP, and Video applications

Application	Codec/size	$\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$	$\zeta^c_k(pl)$	$\zeta^c_k(d)$	$w_{pl.j}$	$w_{d.j}$
Voice	G.711	4.48	0.03	0.0075	0.75	0.25
	G.729	4.20	0.03	0.0075	0.75	0.25
	GSM EFR	4.44	0.075	0.0033	0.4	0.6
FTP	20Mb	5.0	0.99	0.0429	0.5	0.5
Video	JM	3.98	0.031	0.011	0.7	0.3

2.5.1.3 Utility Function Representation of User Satisfaction for VoIP Applications

Now that we have analyzed behavior of users towards the service quality using objective testing methods, we are in position to suggest a function that can capture the user behavior similar to the one from subjective or objective measurements. Since objective measurements are carried out for different codecs, packet loss, and delay values, therefore first two components of the proposed user utility (Equation 2.1) are adequate to capture user satisfaction.

$$u_{j,k,c}(o,n) := \bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)\prod_{l\in L}(\nu_{jl,o}(k,c,n))^{w_{jl}} \tag{2.5}$$

where $\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$ corresponds to the maximum achieveable MOS value, when the user is associated to codec c, and this utility is given by a step like function[1].$\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$ is tuned by the $\prod_{l\in L}(\nu_{jl,o}(k,c,n))^{w_{jl}}$ utility component. The control parameters for this utility component take different values for different codecs, which are given in the Table 2.4.

2.5.1.4 Validation of Utility Function for VoIP Application

In this section we validate the *proposed utility function* for VoIP application by comparing the plots attained from the *utility function* to the plots we get from *objective measurements* (through simulations), this is shown in Fig 2.7, where the correlation clearly strengthens the claim that proposed utility function for VoIP applications estimates the user satisfaction with appreciable confidence level. The details about estimated MOS values attained from the proposed utility function (for GSM EFR codec) is given in Table 2.5. The MOS and utility function values for other codecs are omitted due to somewhat similar variation values between the utility based and objective measurement values. However, their values are represented by Fig 2.6. As

Voice codec GSM EFR					
No.	PL	DL	MOS(U)	MOS(S)	Diff.
1	0	0	4.44	4.44	0.00
2	2	0	4.16	4.26	0.10
3	6	0	3.73	3.65	0.08
4	10	0	3.48	3.42	0.06
5	0	20	4.30	4.39	0.09
6	0	30	4.20	4.36	0.16
7	0	50	4.03	4.29	0.26
8	0	75	3.89	4.20	0.31
9	2	20	3.99	4.20	0.21
10	4	30	3.70	3.90	0.20
11	2	50	3.75	4.00	0.25
12	4	75	3.37	3.85	0.18
13	6	100	2.98	2.73	-0.26
14	4	175	2.73	2.49	-0.24
15	4	200	2.64	2.32	-0.32
16	6	250	2.23	1.75	-0.48
17	6	50	3.30	3.09	-0.21
18	8	50	3.15	2.84	-0.31

Table 2.5: Comparison of Analytical Model estimates and Objective Measurement (MOS).
DL: Packet Delay(sec); PL: Packet Loss(%); Diff.: Difference of objective MOS & Analytical Model; MOS(S): MOS from simulations; MOS(U): MOS from utility function.

evident from the figure that most of the points overlap well i.e., few points map exactly, for few MOS values the proposed utility function partially underestimates or overestimates the objective MOS values. Observing the figures Fig 2.7 & 2.6 and Table 2.5, we can confidently conclude that proposed utility function estimate the user satisfaction very similar to the estimated values that we get from objective or subjective experimentations.
Note: To get the best fit and find the values on unknown controlling variables, we use the optimization tool of Mathematica.
In Table 7.1, we also define the ranges of parameter values of different codecs. These values are obtained from the objective measurement and function results. It should further be noted

[1]The details of such step like function are given in subsection-2.5.1.2.

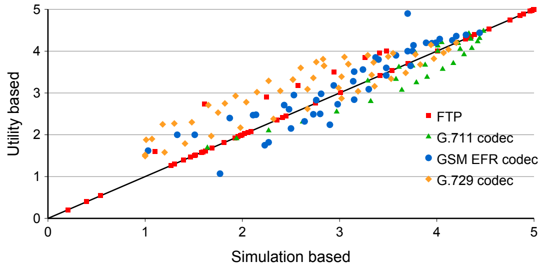


Figure 2.6: Correlation figure - Figure shows the correlation of objective measurement values and the values attained from the proposed utility function for VoIP and FTP applications. For VoIP applications, the correlation values for three different codecs are observed. In case of FTP application, the objective measurements values and utility function values are the scaled values after the transformation function values is applied.

that the user type mapping over MOS curves is carried out based on ITU-T standard definition of user satisfaction e.g., excellent users $\sim$ very satisfied $\sim$ with MOS value 4.3 and above.

2.5.2 NRT Applications

Interactive and Background traffic classes can be combined in NRT applications, which are commonly termed as *elastic* applications, these application are further divided into *symmetric* and *asymmetric non-real-time* applications. Examples of *non-real-time symmetric* applications include *Internet relay chat*, and *non-real-time asymmetric applications* include *FTP*, *Telnet*, *E-mail*, *browsing etc*. Generally *non-real-time* applications do not have stringent requirements for bandwidth and delay. Such application can run even with minimal amount of available bandwidth, therefore, call admission control may not be needed in this case. TCP based (FTP) non-real-time applications can make an error free delivery of data possible through a network which introduces impairments like packet loss, packet delay, packet delay variations, etc. The error free delivery of contents is achieved through ARQ mechanism of TCP. This error control mechanism comes at the cost of reduction in data transfer rate for certain period of times as well as wastage of bandwidth resources. The reduction in data transfer rate finally contributes towards waiting time. This necessitates the proper investigation of *how much is the influence of packet loss and packet delay on achievable TCP throughput?* According to literature, TCP throughput is inversely proportional to round trip time of a network. In case of negligible packet loss rate following relation holds i.e., throughput $\leq$ (TCP buffer size) / RTT, where RTT is TCP segment round trip time. But if there are considerable packet losses

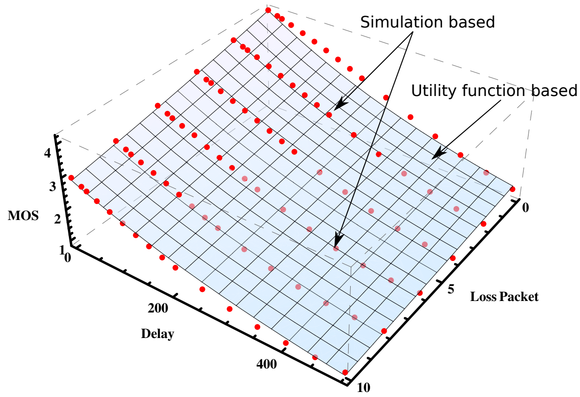


Figure 2.7: Mapping of objective and utility function measurement values for VoIP application - As can be seen that not all the values overlap each other exactly i.e., few utility function values over estimate (e.g., values in the range *zero* packetloss and 200msec delay values) and few utility function values under estimate (e.g., values in the range 10% packetloss and 300msec delay values)

than following relation (which is developed by Mathis and known as Mathis equation) holds i.e., throughput < (MSS/RTT)*(1/sqrt(PLR)), where MSS is the maximum TCP segment size, RTT is the round trip time and PLR is the packet loss rate. However, above relations only show the upper bound of achievable TCP throughput. In order to investigate the more concrete throughput values of TCP in the presence of certain packet delay and packet loss rate, extensive simulations runs are provisioned.

2.5.2.1 User Satisfaction Metric for NRT Application

The performance metric to measure user satisfaction for NRT applications include *throughput*, *data response time*(7), and *MOS*. Although different, these performance measuring parameters are correlated. In this chapter, we choose the MOS value as a performance metric for FTP applications. The motivation for selecting MOS as the performance metric is to have a generalized and common metric for different services.

2.5.2.2 FTP Objective Measurements

On the similar lines as the VoIP application objective measurements, we set up simulation scenario with heterogeneous wireless technologies involving LTE, and WLAN and run lengthy rounds of simulations to analyze the user satisfaction for different values of delay and packet loss.

Simulation Settings and Methodology - This simulation environment also involves the *impairment entity*, and *LTE* in the similar fashion as discussed in the VoIP simulation settings, however in this case, caller and callee are replaced by the FTP server and FTP client. FTP server and client are connected through LTE access network. In our settings, an FTP client downloads a heavy file (of 20MB) through LTE and WLAN access networks. The choice of file size here is dictated by the following facts; i) slow start effect of TCP can be ignored, ii) correlation of TCP throughput and distribution of packet losses within a TCP can be reduced. We artificially inject the packet delays by using the impairment entity, packet delays follow *Normal*

Table 2.6: QoS parameters and ranges for Voice Applications

	G 7.11 Codec	(96kbps)	
Parameters	Range	MOS	Category
	$0ms \sim 50ms$	4.3 and above	Excellent
Delay	50ms $\sim$ 200ms	$3.59 \sim 4.3$	Good
	200ms $\sim$ 300ms	$3.1 \sim 3.59$	Fair
	$0\% \sim 3\%$	4.3 and above	Excellent
Packet Loss	$3\% \sim 10\%$	$3.59 \sim 4.3$	Good
	$10\% \sim 18\%$	$3.1 \sim 3.59$	Fair
	GSM EFR codec	(28.4kbps)	
	$0ms \sim 50ms$	4.3 and above	Excellent
Delay	$50ms \sim 175ms$	$3.59 \sim 4.3$	Good
	$175ms \sim 250ms$	$3.1 \sim 3.59$	Fair
	$0\% \sim 2\%$	4.3 and above	Excellent
Packet Loss	$2\% \sim 8\%$	$3.59 \sim 4.3$	Good
	$8\% \sim 16\%$	$3.1 \sim 3.59$	Fair
	G.729A codec	(40kbps)	
	$0ms \sim 20ms$	4.3 and above	Excellent
Delay	$20ms \sim 125ms$	$3.59 \sim 4.3$	Good
	$125ms \sim 200ms$	$3.1 \sim 3.59$	Fair
	0%	4.3 and above	Excellent
Packet Loss	$0\% \sim 6\%$	$3.59 \sim 4.3$	Good
	$6\% \sim 8\%$	$3.1 \sim 3.59$	Fair

Table 2.7: MOS Value scaling for FTP

Perceived quality	MOS	FTP perceived quality
Excellent	5	Imperceptable
Good	4	Perceptible but not annoying
Fair	3	Slightly annoying
Poor	2	Annoying
Bad	1	Very annoying

distribution. A *bandwidth shaping* of 8Mbps is performed at a router in LTE transport network. We use the most widely used TCP flavor *New Reno* with receiver buffer size of 64KB. Moreover *windows scaling* option of TCP is disabled, *window scaling* option allows TCP maximum congestion window size to grow beyond 64KB. Due to deployment of accumulated acknowledgements, TCP is not very sensitive to the loss of few percent of acknowledgement packets in uplink direction, therefore, effect of packet loss is investigated only in downlink direction. It should also be noticed that processing delay and packet losses in network components (other than impairment entity) are negligibly small. Packet losses are injected based on Bernoulli distribution, packet delays are actually Round Trip Time (RTT) values.

Simulation Results - We analyze the impact of packet loss and delay values on the *user throughput* as shown in Fig 2.9. However *user throughput* does not directly show the user satisfaction, in this connection, we need to translate the *user throughput* values into *user satisfaction*. We carried such translation using the *throughput to MOS mapping approach* detailed below.

Throughput to MOS Transfer Function - For such transfer function, we assume that a user of type k is subscribed to an amount of bandwidth b_k, such that the user remains fully satisfied (has the $MOS = \overline{MOS}$) as long as she receives the bandwidth b_k or $b_k + \tilde{\epsilon}$ (where $\tilde{\epsilon}$ is a small amount of bandwidth), and for any bandwidth less than b_k, the user satisfaction degrades and user reaches the *irritated state*, when the received bandwidth is $\underline{b}_k$. We term the bandwidth range $[\overline{b}_k - \underline{b}_k]$ as *feasible bandwidth range* for user k. This further necessitates a function of degradation and scaling the user satisfaction. We scale the user satisfaction for FTP applications on the similar (as depicted in Table 2.7), whereas the bandwidth dependent component of utility i.e., Equation 2.1 is used as the degradation function between fully satisfied and fully irritated states of user.

Given the *throughput to MOS* transfer function, we now derive the user satisfaction for the achievable data rate (as depicted for different delay and packet loss values in Fig 2.9) in terms of MOS values, this results in Fig 2.8. However, for such transfer function different control parameters of Equation 4.20 take the following values; $\overline{b}_k = 1.265 \times 10^7 kbps$, $\underline{b}_k = 20250.449 kbps$, $\beta = 0.000006$, and $\mu_k = 5$.

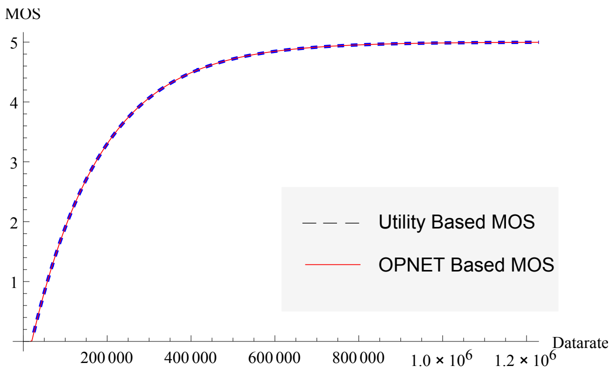


Figure 2.8: Comparison of Utility Based and Objective Measurement Based MOS values for FTP application - The figure presents the mapping of objective measurement values over the proposed utility function values. However, this mapping undergoes the throughput to MOS transformation, thus scaling large throughput values over smaller MOS range results in perfect overlapping.

2.5.2.3 Utility Function Representation of FTP User Satisfaction

We capture the user satisfaction for FTP applications using the proposed utility function given in Equation 2.1. From the simulations and experimentations, what we get is the user throughput and impact of different packet loss and delay on the throughput as shown in Fig 2.9. The $\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)\prod_{l\in L}(\nu_{jl,o}(k,c,n))^{w_{jl}}$ utility components capture the user satisfaction that is comparable to measurement results obtained from the objective testings. Let us first discuss the case, when we are not mapping the throughput over the MOS values, in this case $\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$ component of the utility function takes the constant value that represents the *throughput in lossless conditions*[1] i.e., $\overline{b}_k = 1.265 \times 10^7 kbps$, which is shaped by the $\prod_{l\in L}(\nu_{jl,o}(k,c,n))^{w_{jl}}$ and it is observed that these map very well, as can be seen from the Fig 2.9. To capture the user

[1] Lossless conditions can be defined as the ideal conditions with $zero$ packet loss and delay values

satisfaction in terms of MOS value, we scaled the throughput by mapping it over the MOS [1], the scaled results are presented in Fig 2.8.

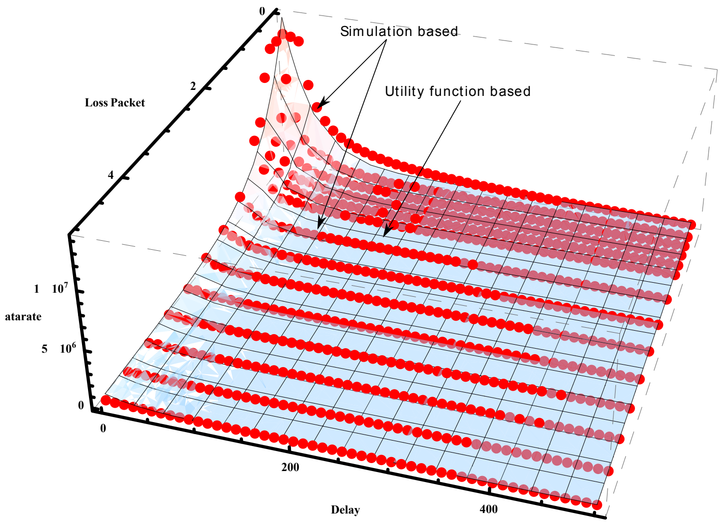


Figure 2.9: Overlapping of utility-based data rate values over the simulation-based data rate for FTP application - The figure presents validation results of the proposed utility function for FTP application. As can be seen that the values from both the objective measurement and utility function measurements map well for most of the delay, packet loss rate values. However deviation of the estimated value proposed by the utility function is observed for packet losses of lesser than 2% and smaller delay values.

2.5.2.4 Validation of Utility Function for FTP Application

In order to validate the proposed utility function against the objective measurements for the FTP applications, the bandwidth utility function component takes the controlling parameter values as given in section 2.5.2.3. The overlapping of the objective measurement values and proposed utility function values shown in Fig 2.9 & 2.8 clearly advocate that the proposed utility function estimate the user satisfaction fairly close to that of the objective measurement. One could observe the exact mapping of the two values in Fig 2.8. The reason for such accurate mapping is the transformation of very large throughput values (x-axis) to the small MOS scale (y-axis), this variation of few kbps in the throughput turns out to be negligible. However, in Table 2.9 we list few of the throughput and MOS mapping values from the objective measurement and

[1] *Note* - We use the similar parameter values for mapping in utility function based measurement,i.e.$\bar{b}_k = 1.265 \times 10^7 kbps$, $\underline{b}_k = 20250.449 kbps$, $\beta = 0.000006$, and $\mu = 5$

the proposed utility function. Thus the results shown in Fig 2.9, 2.8, and Table 2.9 indicate that the utility function estimates the user satisfaction similar to the objective measurement and hence validate the proposed utility function.

2.5.3 Video Streaming Applications

In this section, we focus on validating the suitability of the proposed utility function for video applications.

2.5.3.1 Introduction

Similar to VoIP, video quality at receiving end can be determined using subjective as well as objective evaluation techniques. Most commonly used objective evaluations produce PSNR and Structural similarity (Ssim) as output video quality metrics.

Definition 1. *PSNR defines the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation. When comparing two video files, the signal is the original file and noise is the error which occurs due to compression or during transmission over the network. In the context of video quality evaluation, PSNR is taken as an approximation to human eye perception of image quality. It is measured in decibel units (dB).*

Definition 2. *The Structural Similarity (Ssim) index is a novel method for measuring the similarity between two images. It takes the original undistorted image as a reference and provides the quality measure of the compressed/distorted image. Ssim index value ranges from -1 to 1. The higher the Ssim index value the higher the similarity between the two comparing images. For videos Ssim index is computed image by image (30).*

2.5.3.2 Objective Video Service Measurement

In this section, we detail the simulation setup and methodology that we adopted to carryout the objective measurements for video applications.

Methodology and Simulation Setup - In this work, we use PSNR as video quality metric. It is mainly because of its widespread use in scientific literature. Moreover we calculate the MOS value based on PSNR value. There are several parameters which decide the sensitivity of the end user video quality to network impairments, such as;

- Type encoding - It is due to the fact that encoding schemes differentiate among frames based on their importance in the decoding process. Hence a loss of more important key frames deteriorates reconstructed video quality much more than the loss of less important non-key frame.
- Error concealment method,
- Frames per second,
- MTU size of transport network,
- Pre-filtration of codec, etc.

However a thorough study of the impact of all other above parameters on video file transmitted over a wireless network in the presence of additional IP impairments is beyond the scope of this work. We consider a reference video sequence called *Highway* for this work. The motivation to use this video sequence its repeated reference in a large number of studies in video encoding and quality evaluation e.g., *Video Quality Experts Group*(31). This video sequence has been encoded in $H.264$ format using the JM codec (32) with CIF resolution (352×288) using a target bit rate of $256kbps$. $H.264$ codec has been selected because its widespread use can be seen in future communication devices. The reference video sequence has in total 2000 frames and frame rate of $30fps$. A key frame is inserted after every $10th$ frame which provides good error recovery capabilities. An excellent video quality is indicated by $38.9dB$ as an average PSNR value of the encoded video sequence. The video file is transmitted over the IP network considering MTU size of 1024 bytes. At the receiving end, the video file is reconstructed from the received IP packets. The reconstructed video file might have errors due to packet losses and delays in the transport IP network. Results presented in this work have been taken from the OPNET simulation setup.

This simulation setup has two parts. First part has been developed using OPNET which includes an implementation of the LTE access network. In-fact all basic E-UTRAN and EPC network entities related to LTE have been implemented in this simulation environment. Second part of the simulation setup is derived from EvalVid (33). EvalVid is a framework which can be used for video quality evaluation. It provides both PSNR as well as MOS values of the reconstructed video file. The reason to bring Evalvid into play is its flexibility to be used in conjunction to simulation environments like ns-2 and OPNET. None of the other available video evaluation tools provide such an interface. Target of this task is to get video quality metric for video file which is transmitted over LTE access network. The transport network part of LTE artificially introduces IP impairments to the transmitted video file. These IP impairments are introduced with the help of the *impairment entity* that resides in the transport network. As explained earlier that the *impairment entity* imposes certain packet delays, packet delay variations as well as packet losses (according to predefined impairment profiles) on all packets flowing through a transport link. For this work, *Normal distribution* has been considered for packet delays and packet delay variations. This choice is based on empirical study of big IP networks. Moreover packet losses are injected using *Bernoulli distribution*.

Following sequence of action leads to video quality metric for a particular value of mean packet delay and packet loss rate. EvalVid tools are used to generate a file which includes information about packets (e.g., *packet type*, *size*, *count*, etc.). These are the packets which would carry video frames if video file is transmitted over an IP network in real world scenario. *Packet size* and *type* information is used to transmit the same number, type and size of packets over LTE access network using OPNET simulator. IP impairment entity injects specified *packet delays* and *packet loss rate* in the above generated packet stream. Associated information of received packets (e.g., *packet end-to-end delay*, *jitter*, *type* and *sequence number of lost packets*) is used to reconstruct video file. This task is performed using EvalVid tools. A *Play-out buffer length* of $250ms$ is used in this step. The reconstructed video file is then compared against the raw formatted reference video file to compute PSNR values frame by frame. It tells about the noise introduced due to encoding scheme. Reference $H.264$ encoded video file is also compared against the raw formatted reference video file to compute PSNR values frame by frame. It tells about the noise produced by both *encoding* as well as *transmission errors*. Video quality metric is computed by evaluating the difference between quality of the $H.264$ encoded video file and the reconstructed video file. The MOS of every single frame of the reconstructed video file is compared to the MOS of every single frame of the reference video file. In the end average MOS value of whole video file is output. For PSNR to MOS translation following table is used (34). Fig 2.10 shows the *video user* satisfaction for different packet loss and delay values.

2.5.3.3 Utility Function Representation of Video User Satisfaction

We capture the user satisfaction for video streaming applications using the proposed utility function given in Equation 2.1 on very similar lines to that of VoIP applications[1]. The first two

[1]For details, refer to VoIP application section i.e., 2.5.1

components of user utility function estimate the user satisfaction for different values of packet loss and delays. For video application, the control parameters of the proposed utility function are listed in Table 2.4. In order to validate the proposed utility function, we overlap the results obtained from the utility-based measurement over the simulation-based measurements. It is observed that the proposed utility function estimates the *video user* satisfaction very similar to the satisfaction values from experimentation, this is evident from the Fig 2.10.

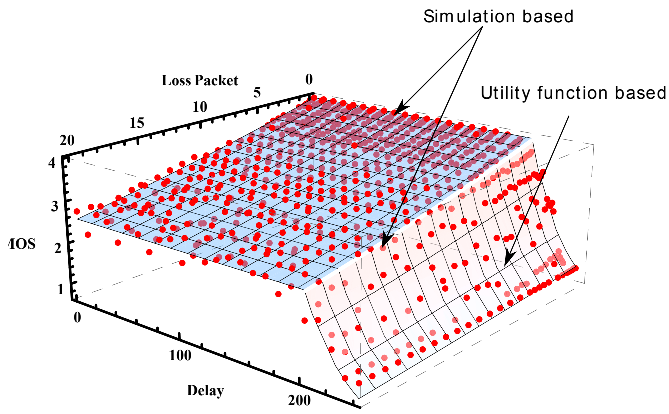


Figure 2.10: Overlapping of utility-based MOS values over the simulation-based MOS values for video application - The figure shows validation results, where one can observe that for almost all the delay and packet loss values, the proposed utility function map very well. Thus validating the proposed utility function estimates the user satisfaction function with appreciable accuracy.

2.6 Extension of Utility Function for Handover and Codec Switchover

Owing to the short term user contractual agreements with the operators and greater mobility support in future wireless networks, it is envisioned that at different times a user is associated to network technologies of different characteristics (and different codecs for voice and video applications). Heterogeneous wireless network technologies and various codecs exhibit different MOS behaviors to packet loss and delay values, therefore it is important to capture the QoE degradations introduced by the handover and switch over costs. To capture these effects, we extend the proposed utility function.

No.	Network	Codec	Ppl	Subj.	Model	Diff.
1	W→H	722.2	0	4.27	4.27	0.00
2	W	722.2	0	4.49	4.49	0.00
3	W→H(b.)	722.2→711	0	2.34	2.35	-0.01
4	H→W(a.)	711→722.2	0	2.55	3.98	-1.43
5	H→W	711	10	2.42	2.158	0.26
6	W	722.2	10	2.02	2.23	-0.21
7	H→W(b.)	711→722.2	20	1.81	1.339	0.47
8	W→H(a.)	722.2→711	0	2.32	2.33	-0.01
9	W→H	722.2	10	2.34	2.12	0.22
10	H	711	0	2.95	2.95	0.00
11	H→W	711	0	3.28	3.10	0.18
12	H	711	10	1.96	1.95	0.01
13	W→H(b.)	722.2→711	20	1.38	1.28	0.1
14	W	722.2	20	1.27	1.11	0.16
15	H	711	20	1.45	1.3	0.15

Table 2.8: Comparison of Analytical Model estimates and Auditory Judgments (MOS).
Ppl: Packet loss in %; Diff.: Difference of subjective MOS & Utility-based Model MOS; W: WLAN; H: HSDPA; →: Handover/Changeover, a./b. : Changeover before/after handover.

2.7 Utility Function with Switching Costs

In this section, we take into consideration handover costs and codec switching costs in the utility function. Thus now the proposed user utility function is the function of packet loss, handover, codec switchover costs but also reputation and security indexes of the operator. Let $u_j(.)$ be the utility function of user j, and is given by

$$\begin{aligned} & u_{j,k,o,c,co,w}(pl, \psi\tilde{\zeta}, \varphi) \\ = \quad & \tilde{u}_o(\frac{b_{k,o,c}}{n_{o,k,c}})\mu^{\bar{co}}_{\bar{w},k,o,c}e^{-\sigma(pl^{\bar{co}}_{\bar{w},k,o,c}+\psi(\frac{b_{k,o,c}}{n_{o,k,c}})\tilde{\zeta}^{\bar{w}}_{w})} \\ & -\psi(\frac{b_{k,o,c}}{n_{o,k,c}})\tilde{\mu}^{co\longrightarrow\bar{co}}_{w\longrightarrow\bar{w}}e^{-pl^{co}_{w,k,o,c}\varphi^{\bar{co}}_{co}} \\ & -\pi_{k,o,c,co,w} - f(r_o, s_o) \end{aligned} \tag{2.6}$$

where $\mu^{\bar{co}}_{\bar{w},k,o,c}$ represents the maximum achievable MOS value in the network technology $\overline{w} \in W$ using codec co for operator o, pl represents the packet loss rate. Here ψ takes the value of 1, when a call handsover from *high bandwidth* to *lower bandwidth* technology or from *wideband* codec to *narrowband* codec and -1 otherwise. $\tilde{\mu}^{co \longrightarrow \bar{co}}_{w \longrightarrow \bar{w}}$ represents the constant gain / loss of MOS value when codec switch over takes place and their values are dictated by the network and codec characteristics. The function π represents the pricing function to the users. The term $\tilde{u}_{j,o}\left(\frac{b_{o,k,c}}{n_{o,k}}\right)$ is a function of network state $n = (n_{o,k,co,w})_{o,k,c,co,w}$ and the offered bandwidth $b_{o,k,c}$ by the operator o. The collection n is a vector that represents total number of users those request the service of specific class under specific codec and handover. Similar to the associated independent utility attribute, the function f is a generic function that takes into consideration the reputation and the security of the operator (an increasing function in each of the component) or any independent associated attribute. However, the functions to represent the user satisfaction for such attribute should carefully be modelled. σ measures the decay rate of user's satisfaction.

It is noted that $\mu^{\bar{co}}_{\bar{w},k,o,c} \neq \mu^{co}_{w,k,o,c}$, where $(co, w) \neq (\bar{co}, \bar{w})$, it shows that users quality rating is dependent on the networking conditions e.g., WiFi with stable network bandwidth along with a superior quality wideband codec sampled at $16kHz$ provides best results. Whereas HSDPA with its fluctuating bandwidth due to base station based scheduling and high link layer retransmissions is expected to provide lesser quality even if superior quality codecs are used (11). Value of $\tilde{\zeta}$ is dictated by the handover type i.e., $\tilde{\zeta}_{bm} > \tilde{\zeta}_{mb}$, where bm, and mb represents the *break before make*, and *make before break* approaches respectively. Generally the value of σ is dictated by the application type and the underlying network technology.

Since the proposed utility function is monotonically decreasing in all the considered parameters i.e., with increase in a considered parameter value the user gets more irritated. We therefore, introduce the term *cost value* that represent the aggregated effect of different parameter values. Let L represents the set of considered parameters, then $L = \{pl, \tilde{\zeta}, \varphi\}$. We define the cost value as:

$$\mathcal{K} = \sum_{l \in L} z_l \tag{2.7}$$

where z_l is the individual cost contribution of parameter l. Thus the function can now be written as:

$$u_j(\mathcal{K}, pl, \psi\tilde{\zeta}, \varphi) = \begin{cases} 0 \quad \text{if} \quad \mathcal{K} \geq \mathcal{K}_{max} \\ \mu_w^{co} + \psi\tilde{\mu}_w^{\bar{co}} \quad \text{if} \quad \mathcal{K} < \mathcal{K}_{ac} \\ \mu_w^{co} e^{-\sigma(\mathcal{K} - pl\varphi)} - \psi\tilde{\mu}_w^{\bar{co}} e^{\mathcal{K} - (pl + \psi\tilde{\zeta})} \quad \text{if} \quad \mathcal{K}_{ac} < \mathcal{K} < \mathcal{K}_{max} \end{cases} \tag{2.8}$$

where $\mu_w^{co} + \psi\tilde{\mu}_w^{\bar{co}}$ represents the maximum achievable utility depending on the user context and users association with a technology and codec for the voice call, $\mathcal{K}_{max}$ is the maximum tolerable cost by the user j, it can also be interpreted as cost threshold, above which user is no more satisfied. $\mathcal{K}_{ac}$ represents the acceptable cost of the user, and it is taken as the ideal cost threshold for maximum satisfaction of user.

Consider the $u_j(\mathcal{K})$ of user j, where $\mathcal{K}$ is the aggregated cost computed from the technical characteristics of operators' offers. This dictates that there always exists an upper bound for the considered parameters due to technological constraints or user preferences / requirements. Such bounds define different regions of utilities as shown in Equation 2.8. Where the two obvious regions are translated as fully satisfied and fully irritated regions bounded by $\mathcal{K} < \mathcal{K}_{ac}$ and $\mathcal{K} \geq \mathcal{K}_{max}$ respectively. Third region bounded by $\mathcal{K}_{ac} < \mathcal{K} < \mathcal{K}_{max}$ shows the satisfaction behavior of user following the function given in Equation 2.8. All the three regions define the user satisfaction of users. Let us scale the user satisfaction on the same lines as the ITU standard for QoE measurements. We scale the satisfaction function between $0 \sim 5$, where 5 represents the maximum and 0 minimum user satisfaction i.e., $u_j(\mathcal{K}) \in [0, 5]$.

The region of proposed utility function represented by $\mu_w^{c} e^{-\sigma(\mathcal{K} + pl\varphi)} - \psi\tilde{\mu}_w^{\tilde{c}} e^{\mathcal{K} - (pl + \psi\tilde{\zeta})}$ should be twice differentiable on interval $[\mathcal{K}_{ac}, \mathcal{K}_{max}]$. Fulfilling this requirement guarantees that the user satisfaction level does not change drastically with a small change in the $\mathcal{K}$ value and marginal satisfaction is regular.

Similarly, increase in value of the considered parameter, say packet loss ratio above certain threshold results in near *zero* user satisfaction, therefore user behaves indifferently for parameters values above some threshold value. This implies the convexity of the satisfaction curve. In addition the utility function satisfies the following requirements:

$$u_j(\mathcal{K}) = 0 \qquad \forall\, \mathcal{K} \geq \mathcal{K}_{max} \tag{2.9}$$

$$u_j(\mathcal{K}) = \mu_{max} \qquad \forall \mathcal{K} < \mathcal{K}_{ac} \tag{2.10}$$

where μ_{max} represents the maximum user utility.

2.8 Model Criteria and Validation with Switching Cost Effect

In this section, we highlight the impact of single and multiple attribute values variation on the user satisfaction, which we then extend to multiple attribute scenario.

2.8.1 Single Attribute Utility Function

In a single criterion utility function, the utility function captures user satisfaction for the possible degradation effect introduced by the criterion. Consider a scenario, where a static user experiences $zero$ delay, no vertical handover and no codec switchovers. In such a case users satisfaction is fully dependent on the packet loss rate.

$$u_j(pl) := \mu_w^{co} e^{-\sigma.pl} \qquad \forall pl \in [pl_{ac}, pl_{max}] \tag{2.11}$$

Let us consider that the user is associated to a specific codec, say $co = G.711$, and with network technology $w = HSDPA$, here μ_w^{co} represents the maximum achievable MOS value in this scenario, which is achievable for packet loss less than pl_{ac}. We plot the MOS curve for this scenario in Fig 2.11 (the plots are generated through proposed utility function). In addition we also investigate single attribute utility function for a different network technology $w = WLAN$, and broadband codec $G722$, and plot the user satisfaction curve for this scenario as well in Fig 2.11. As can be observed that $\mu_{WLAN}^{G722} > \mu_{HSDPA}^{G711}$, this is because of the fact that HSDPA link exhibits more fluctuations than WiFi due to shared downlink. The primary reasons for this is base station scheduling which allocate resources only to the users having good wireless link conditions. WiFi is also interference limited technology and link transmission is greatly dependent on the simultaneous demand of the wireless channel resources. One more point to be noticed here is that $\sigma-$value in WLAN is greater than in HSDPA, which results in greater decay of MOS value with increasing packet loss. These results from the proposed utility function behavior are validated for this scenario (see # 2, 6, 10, 12, 14, and 15 in Table 2.8) and various scenarios discussed in later sections i.e., keeping the mentioned setting against the subjective measurement ratings (12) for different values of packet loss ($0\%, 10\%, 20\%$).

2.8.2 Multiple Attributes Utility Function

In a multiple attribute utility function, the utility function captures user satisfaction for the possible degradation effect introduced by the combined effect of multiple criteria. Now we

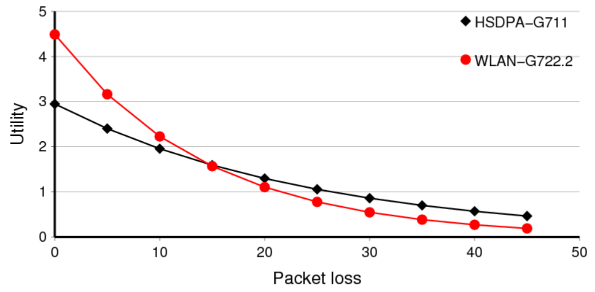


Figure 2.11: Utility values in HSDPA (G.711) and WLAN (G722.2) for different packet loss values in single-attribute scenario - The figure shows user satisfaction in single criteria configuration i.e., considering all the other parameter values lie with satisfactory range and the packet loss values change only. One can observe that the maximum achievable MOS value for different codec and technologies vary. These ideal values are verified against the values obtained from subjective experimentations.

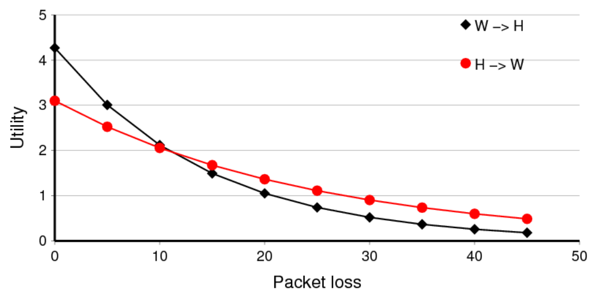


Figure 2.12: Utility values in HSDPA and WLAN for different packet loss values in multi-attribute scenario - In this figure, user satisfaction, when connected to different technologies and codecs is observed for different values of packetloss and when she hands over to a different technology. The user satisfaction behavior in this figure can be compared against the experimental results presented in Table 2.8.

consider a scenario, where a user experiences vertical handovers, and her satisfaction is influenced by both packet loss and handover costs, given by:

$$u_j(pl) := \mu_w^{co} e^{-\sigma.(pl+\psi\tilde{\zeta})} \qquad \forall pl \in [pl_{ac}, pl_{max}] \tag{2.12}$$

Let us consider a specific scenario, where a user is initially associated with network technology say WLAN and codec $G722.2$, as discussed in the previous subsection the maximum achieveable MOS value for this user is $\mu_{WLAN}^{G722.2}$, now that user experiences a vertical handsover to $HSDPA$, she experiences a further degradation (this degradation is represented by $\psi\tilde{\zeta}$, in this case $\psi = -1$). We plot the MOS curve for this scenario as shown in Fig 2.12. The plot

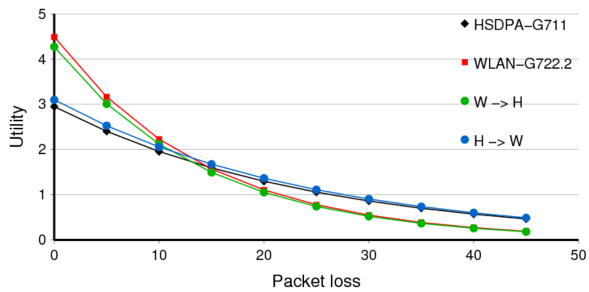


Figure 2.13: Plots of Utility for single and multi-attribute scenarios - In this figure, we combine the Fig 2.11 & 2.12 in order to investigate the impact of second attribute i.e., handover costs. As can be seen that the curves are slightly shifted and this shift is introduced by the handover costs. However, for high packet losses these curves converge, which is no interest for the analysis owing to the fact that utility is degraded to an unacceptable extent for high packetloss values.

resembles exactly the one shown in Fig 2.11 for different value of packet loss, but shifted by a small value representing the handover cost, the similar behavior as that from the subjective measurements (see # 1, 2, 6, and 9 in table-2.8). In the similar fashion we plot MOS curve for users initially associated to HSDPA network technology and handsover to WLAN network technology, such handover introduces a gain to users satisfaction (therefore $\psi = 1$), the results form the utility function match those from the subjective measurements (see # 5, 10, 11, and 12 in table-2.8). Equation 2.12 captures user satisfaction for both mentioned scenarios for multiple attribute utility function. In general Fig 2.12 presents somewhat similar behavior as in Fig 2.13 shifted by the cost of handover in either direction depending on the value of ψ.

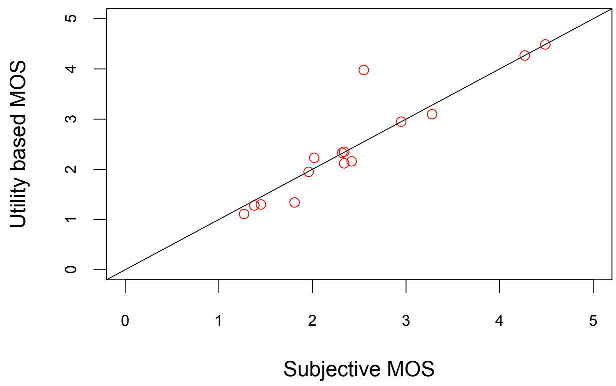


Figure 2.14: Relationship of Model quality estimation and user quality ratings (correlation $r = 0.923$**)** - The figure shows that most of the points lie near the diagonal, which advocates that the proposed utility function estimates that user satisfaction to satisfactory level.

2.9 Experimental Setup for Extended Utility Function

In this section, we discuss our experimental methodology for carrying out the controlled experiments and then conduct auditory tests for NGMN conditions.

2.9.1 Mobisense Testbed

In order to perform quality of experience study, we rely on Mobisense testbed which was designed to investigate user perceived quality in NGMN using VoIP as the primary application. The testbed depicted in Fig 2.15 allows mobile clients to perform network handovers and voice codec changeover while keeping on-going calls. The testbed uses Mobile IPv4 as a solution to enable seamless handovers between different radio access technologies (35). Thus, the main network elements of the testbed are the Mobile Node (MN), the Corresponding node (CN) and the Mobile IPv4 Home Agent (HA). The setup includes various different access technologies such as WLAN/WiFi, UMTS/HSDPA and Flash-OFDM that are used to emulate an integrated NGMN environment.

The CN and MN were deployed on laptops with linux 2.6.18.2 and HA was configured on a *Cisco 2620XM* router with *Cisco IOS 12.2(18r)*. Based on SIP protocol we choose `PJPROJECT` (36) framework as voip client to play speech files. We employed seamless codec switching scheme by Wältermann et al. (37). The detailed description of design and the capabilities of Mobisense testbed are outlined in (38).

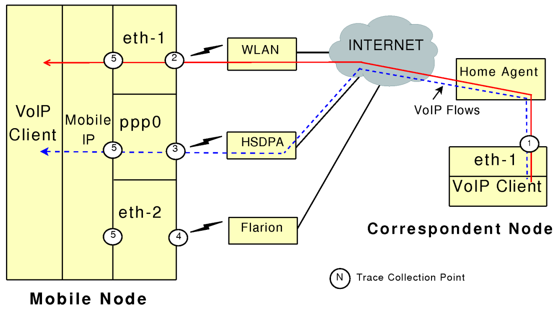


Figure 2.15: Mobisense experimental setup for VoIP services in NGMNs

2.9.2 Methodology

We pre-selected NGMN conditions with the combination of (i) Network handovers between different technologies, (ii) Codec-switching between narrowband codec and wideband codec, and (iii) Different packet loss rates. We use ITU-T G.711 log PCM codec at 64 kb/s for narrowband (NB) with native packet loss concealment and ITU-T G.722.2 (AMR-WB) codec at 23.05 kb/s for wideband transmission. For benchmarking purposes we select few conditions with a single network, a single codec and 0% packet loss. We establish the quality bounds by using these benchmark conditions. Of course one could argue why not to test all combinations but carrying out a full factorial combination of subjective tests is practically infeasible. We use `netem` packet shaper for degrading VoIP packets as shown in Fig 2.15.

All calls were initiated at CN and terminated at MN. During on-going calls network conditions were imposed depending upon the requirements of network handovers or codec switching. At MN, speech samples were collected and processed for subjected tests according to ITU-T P.800 (39). Further we select speech samples for both male and female speakers to obtain a balance set of speech samples. These samples were then presented to 24 subjects for quality assessment. For the quality rating, 5-point Mean Opinion Score (MOS) scale was used. More details of these tests can be found in (11). The overall assessment along with conditions is listed in table 2.8.

2.10 Extended Utility Function Validation

In this section, we compare subjective ratings with our model predictions, the results for validation are presented in Table 2.8. In principle the model should be able to predict estimations for most of the conditions. We first check correlation of the predicted values of our model with

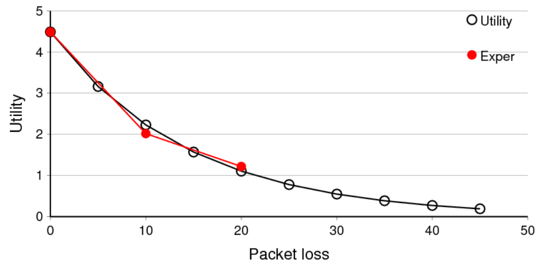


Figure 2.16: User associated with WLAN & G722.2 (No Handover/codec switchover

the subjective test ratings obtained in Table 2.8. The results are shown in Figure 2.14. The concentration of most of the points around the diagonal line is an indicator of a good match between model predicted values and the actual ground truth obtained from the subjects. There is a correlation of 0.923 between model predicted values and the subjective ratings.

We note that for the conditions # 1, 2, 3, 8 10 and 12 in Table 2.8, our model perfectly match the subjective ratings. For conditions #5, 9, 11, 14 and 15 model is off by maximum of 0.26 MOS value. However, inspite the fact that we see a high correlation we have certain conditions e.g., condition #4 and 7 where our model deviates from the subjective ratings. We plot different curves for both the utility function and experimental data in different scenarios so that behavior of utility function for different parameters can be investigated. In Fig 2.16, we consider the scenario where the user is associated to WLAN and G722.2, in this scenario we study the impact of packet loss rate. As evident from the Figure-2.16 proposed utility function almost overlaps the experimental results for low packet loss values, very small deviation is observed, when packet loss rate approaches 20%. Although experimental results are not available for greater packet loss than 20%, the proposed model can confidently estimate the behavior for higher packet loss values. A number of similar curves were obtained for scenarios like i) user associated to HSDPA and G711 with experiencing no handover and codec switch over, ii) user associated to WLAN, G722.2 and experiencing handover to HSDPA, iii) user associated with HSDPA and handsover to WLAN, iv) Codec switchover, v) Simultaneous codec switchover and network handover, etc. In all the mentioned scenario user utility function was validated against the experimental results.

2.10.1 The Impact of Service Prices on User Satisfaction - A Brief Overview

In this section, we demonstrate the impact of service prices in addition to other service affecting parameters. In this connection, we study the user behavior in single and two operators scenarios.

2.10.1.1 Single Operator Scenario

In Fig 2.17, we investigate the user satisfaction in a single operator scenario, in this settings *excellent*, and *fair* type users are considered. The users are characterized by their maximum service valuation (π_k of price based utility in Equation 2.1) i.e., $\pi_{excellent} = 7$ and $\pi_{fair} = 5$. The sensitivity of the user satisfaction towards price and offered QoS can be observed for the two user types. Operator translates the offered QoS in two parameters, delay and packet loss values. Given the packet loss value 1.2%, and different delay values (given in Fig 2.17), utility of fair user approaches $zero$ quicker when compared to excellent user for higher service prices. The result justifies the realistic behavior of different user types e.g., a fair user is more satisfied for less prices than an excellent users.

We also investigate the operator competitive strategies for a single user request in Fig 2.18. In this setting, we assume that the two operators are:

- **Mobile Virtual Network Operator** - the organization that borrows resources (infrastructure or spectrum, etc.) from the network provider and some amount (*access fee*), is paid to Network Provider (NP) against the resources borrowed. This dictates that MVNO incurs higher costs than network provider.
- **Mobile Network provider** - incurs lower operation costs and higher deployment costs, however constant deployment costs are assumed to be normalized to $zero$.

Note: More on these operator types can be found in Chapter 3.

2.10.1.2 Two Operator Scenario

The two operators own LTE and WLAN infrastructure in a geographical area a covering the user j, and compete for the user request. Operators compete with different bids[1]. The probability that operator wins the user request increases with an increasing MOS values, which in turn derives the operators' strategies. In this special case of MVNO and NP competition, the bid

[1] where the bid comprises QoS parameters and service price values

strategies and equilibrium solution is greatly influenced by their incurring costs. We assume that the incurring cost of MVNO is 1, and is greater than the normalized *zero* cost of network provider[1], this and the equilibrium solution is evident from the Fig 2.18.

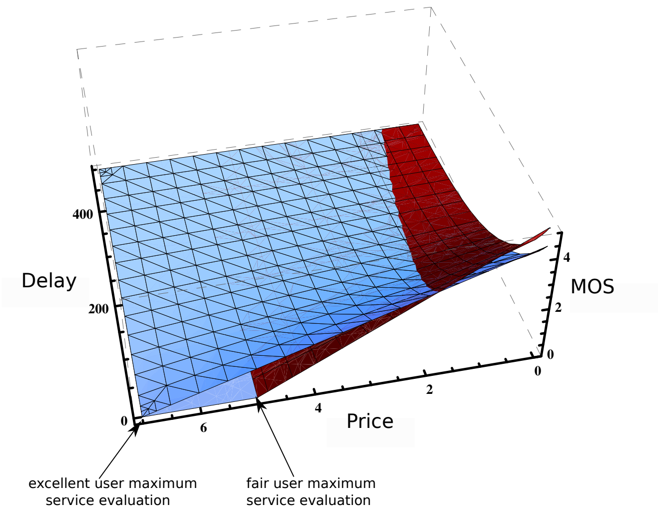


Figure 2.17: Utility of two different users for different values of Quality parameters and price offers (*Red mesh* $\rightarrow$ *fair user, Light blue mesh* $\rightarrow$ *excellent user*)

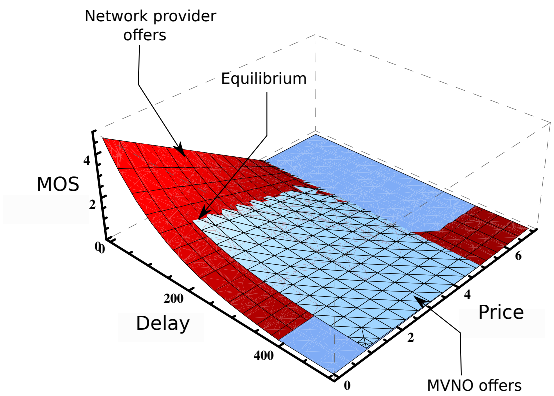


Figure 2.18: Expected utility of user under the offers from two different operator offers (*Red mesh* $\rightarrow$ *network provider, Light blue mesh* $\rightarrow$ *MVNO*)

[1] constant deployment cost of network provider is normalized to *zero*

2.11 User Equilibrium Characterization

The user satisfaction function is expressed in function of $pl, \psi, \tilde{\zeta}, \varphi$ and the type, the class, the codec and the handover. We assume that the performance index pl decreases with the number of users $n_{o,k,c}$. We propose the following form:

$$\begin{aligned} u_{j,o,k,c,co,w}(pl, \psi, \tilde{\zeta}, \varphi) = \mu^{\bar{co}}_{\bar{w},k,o,c} e^{-\sigma(pl^{\bar{co}}_{\bar{w},k,o,c} + \psi(\frac{b_{k,o,c}}{n_{o,k,c}})\tilde{\zeta}^{\bar{w}}_{w})} \\ -\psi(\frac{b_{k,o,c}}{n_{o,k,c}})\tilde{\mu}^{co \longrightarrow \bar{co}}_{w \longrightarrow \bar{w}} e^{-pl^{co}_{w,k,o,c}\varphi^{\bar{co}}_{co}} \end{aligned} \tag{2.13}$$

Now, we formulate the user problem based on the utility functions. Each user j optimizes u_j depending on its codec, handover, type, class of services, and operator. By fixing the operators offer (prices, technology, network availability, etc.), we analyze the interaction between the users in an autonomous and self-optimizing manner. We use the notion of equilibrium (Cournot, Nash, correlated, sequential, hierarchy, etc.) which characterizes the outcomes. Here we restrict our attention to the packet loss pl component but the delay function can be incorporated as well.

- The equilibria in absence of handover: In this case, we omit the index w. A pure equilibrium is a configuration of choices of users, the total number of user profiles with specific codec, type, class represented by $(n_{o,k,c,co})_{o,k,c,co}$ such that if user j moves to $(\bar{o}, \bar{co})$

  $$u_{j,o,k,c,co}(n_{o,k,c,co}) \geq u_{j,\bar{o},k,c,\bar{co}}(n'_{\bar{o},k,c,\bar{co}})$$

  where $n'_{o,k,c,co} = n_{o,k,c,co} - 1$ if user j has moved from (o, co), $n_{o,k,c,co} + 1$ if user moves to (o, co) and equal to $n_{o,k,c,co}$ if no move.

- The equilibria in absence of codec: In this case, we omit the index co. A pure equilibrium is a configuration of choices of users, the total number of user profiles with specific handover, type, class represented by $(n_{o,k,c,w})_{o,k,c,w}$ such that if user j moves to $(\bar{o}, w)$

  $$u_{j,o,k,c,w}(n_{o,k,c,w}) \geq u_{j,\bar{o},k,c,\bar{w}}(n'_{\bar{o},k,c,\bar{w}})$$

  where $n'_{o,k,c,w} = n_{o,k,c,w} - 1$ if user j has moved from (o, w), $n_{o,k,c,w} + 1$ if user moves to (o, w) and equal to $n_{o,k,c,co,w}$ if no moves.

- The equilibria in presence of both handover and codec switchover:

In this case, we take on both indexes w, co. A pure equilibrium is a configuration of choices of users, the total number of user profiles with specific codec, type, class represented by $(n_{o,k,c,co,w})_{o,k,c,co,w}$ such that if user j moves to $(\bar{o}, \bar{co}, \bar{w})$

$$u_{j,o,k,c,co,w}(n_{o,k,c,co,w}) \geq u_{j,\bar{o},k,c,\bar{co},\bar{w}}(n'_{\bar{o},k,c,\bar{co},\bar{w}})$$

where $n'_{o,k,c,co,w} = n_{o,k,c,co,w} - 1$ if user j has moved from (o, co, w), $n_{o,k,c,co,w} + 1$ if user moves to (o, co, w) and equal to $n_{o,k,c,co,w}$ if no move.

For the mixed equilibria of the selection problem with strict support are characterized by the *indifference* conditions. This means that one need the solve the system $u_{j,o,k,c,co,w}(x^*) = \max_{\bar{o},\bar{co},\bar{w}} u_{j,\bar{o},k,c,\bar{co},\bar{w}}(x^*)$ where x^* the vector with component $x^*_{o,k,c,co,w}$ of probabilities of being in the configuration (o, k, c, co, w).

In next subsection we discuss how to learn the user equilibrium using *cost of moves* which relies on the switching and handover costs for any type and class.

2.11.1 Cost of Learning

In this subsection, we introduce a novel way of learning under switching cost called "Cost-To-Learn". Usually in learning in games or in machine learning (reinforcement learning, best reply, fictitious play, gradient-descent/ascent based learning, non-model gradient estimation, Q-learning etc), the cost of switching between the actions, the cost of experimenting another options are not taken into consideration. In this section we take these issues into account and study their effects in the learning outcome. *The idea is that it can be very costly to learn quickly and learning can take some time.* When a player changes its action, there is cost for that. In our scenario, the learning cost can arise in three different situations: (i) handover switch, (ii) codec-switchover, (iii) joint handover-and-codec switch-over. In a more general setting, one can think about a cost to have a new technology or a cost to produce a specific product.

The motivations behind this *cost of learning* approach is that, in many situations, changing, improving the performance, the quality of experience of a user, guaranteeing to a quality of service etc has cost. At a given time t, if user j changed its selection (codec, handover etc) i.e if user j moves, its objective function is translated form the standard utility plus an additional cost for moving from the old configuration to the new one. Then, there is no additional cost to learn if the action remains the same. Assuming that our framework is the class of congestion games for any fixed offering offering options from the operators, one can use the *finite improvement property* which is well-known to be convergent in finite potential games.

To exploit the dynamic nature of learning processes, we adopt the framework of dynamic games. In it, each user act several times and adapt its strategy based on the past measurement and/or observations. In contrast to static games in which the inefficiency of *equilibria* may arise in many congestion-like games, dynamic games allows us to address the question of *emergence of cooperation* and *fairness issues* in the long-run interaction. In our QoE dynamic game, each user adapts its strategy for network selection during the experiments to find out the optimal selection given the offers of the operator. Simultaneously, each operator updates its offers based on the reaction of the users and the other operators. This leads to multi-level optimization scenarios for each of the entities.

Below we describe the reaction to the users in an iterative way. The iterative algorithm works as follows. Initialize the cost of learning to zero for all users. Start with an action profile (a initial network selection of the users and the operators). If we denote by a_t at action profile at time slot t, there are n_o-stages (n_o being the number of users associated to operator o) of move: user 1 moves from $a_{1,t}$ to $a_{1,t+1}$ by solving the following problem:

$$a_{1,t+1} \in \arg\max_{a'_{1,t+1}} \{U_1^t(a'_{1,t+1}, a_{-1,t}) - c_{a_{1,t} \longrightarrow a'_{1,t+1}}\}$$

where $a_{-1,t}$ denotes the vector $(a_{2,t}, \ldots, a_{n_o,t})$ Then, given the optimal choice $a_{1,t+1}$, user 2 optimizes

$$a_{2,t+1} \in \arg\max_{a'_{2,t+1}} \{U_2^t(a'_{2,t+1}, a_{-2,t}) - c_{a_{2,t} \longrightarrow a'_{2,t+1}}\}$$

and so on.

It is important to remark that if the actions are reduced to the handover and the codec and the $c_{a_{1,t} \longrightarrow a'_{1,t+1}}$ chosen as the switching cost then one gets exactly the utility defined above. This allows us to take into consideration the switching cost in learning in games in a natural way. The convergence of cost of learning has been shown in particular class of games in (40).

2.12 Conclusion

We model the utility theory based user satisfaction function, validated it against the subjective and objective measurements for different application types i.e., audio, video, and data. The proposed function is generic enough to be applied to all types of application both in terms of technical and economic aspects. We also studied and extended the proposed satisfaction function to capture the codec switchover and technology handover costs, the extended satisfaction function is validated against the subjective measurements data. The chapter concludes with our investigation of equilibrium criteria for user-centric network selection.

File Transfer Protocol (FTP)					
No.	DR(U)	DR(S)	MOS(U)	MOS(S)	Diff.
1	2.612×10^4	2.683×10^4	0.204	0.203	0.001
2	3.358×10^4	3.279×10^4	0.397	0.400	-0.003
3	4.104×10^4	4.173×10^4	0.542	0.548	-0.006
4	6.891×10^4	6.898×10^4	1.266	1.267	-0.001
5	7.053×10^4	7.068×10^4	1.302	1.305	-0.003
6	7.481×10^4	7.485×10^4	1.396	1.396	0.000
7	8.017×10^4	8.007×10^4	1.509	1.507	0.002
8	8.058×10^4	8.035×10^4	1.518	1.513	0.005
9	8.341×10^4	8.353×10^4	1.577	1.579	0.-002
10	8.440×10^4	8.422×10^4	1.597	1.593	0.004
11	8.512×10^4	8.546×10^4	1.619	1.612	0.007
12	8.886×10^4	8.884×10^4	1.687	1.686	0.001
13	1.012×10^4	1.015×10^4	1.923	1.929	-0.006
14	1.028×10^5	1.028×10^5	1.953	1.953	0.000
15	1.052×10^5	1.053×10^5	1.997	1.999	-0.002
16	1.065×10^5	1.069×10^5	2.020	2.027	-0.007
17	1.103×10^5	1.10×10^5	2.088	2.083	0.005
18	1.263×10^5	1.265×10^5	2.355	2.357	-0.002
19	1.301×10^5	1.305×10^5	2.413	2.419	-0.006
20	1.533×10^5	1.539×10^5	2.750	2.757	-0.007
21	1.735×10^5	1.736×10^5	3.007	3.007	0.000
22	2.252×10^5	2.246×10^5	3.538	3.532	0.006
23	2.456×10^5	2.459×10^5	3.706	3.709	-0.003
24	3.267×10^5	3.272×10^5	4.205	4.207	-0.002
25	3.537×10^5	3.532×10^5	4.323	4.323	0.000
26	3.603×10^5	3.606×10^5	4.350	4.350	0.000
27	3.405×10^5	3.735×10^5	4.388	4.399	-0.011
28	3.802×10^5	3.868×10^5	4.443	4.445	-0.002
29	4.169×10^5	4.162×10^5	4.537	4.535	0.002
30	5.212×10^5	5.206×10^5	4.752	4.751	0.001
31	6.123×10^5	6.149×10^5	4.856	4.858	-0.002
32	6.566×10^5	6.564×10^5	4.890	4.890	0.000
33	9.195×10^5	9.229×10^5	4.977	4.977	0.000
34	1.115×10^6	1.115×10^6	4.993	4.993	0.000
35	2.414×10^5	2.416×10^5	5.000	5.000	0.000

Table 2.9: Comparison of Analytical Model estimates and Objective Measurement (MOS).
DR(S): Datarate from simulations (in kbps); DR(U): Datarate from utility function (in kbps); Diff.: Difference of objective MOS & Analytical Model; MOS(S): MOS from simulations; MOS(U): MOS from utility function.; DL: Packet Delay; PL: Packet Loss.

3

User-Centric Network Selection

The business models of telecommunication operators have traditionally been based on the concept of the so called closed garden: they operate strictly in closed infrastructures and base their revenue generating models on their capacity to retain a set of customers and effectively establish technological and economic barriers to prevent or discourage users from being able to utilize services and resources offered by other operators. However, these barriers may no longer be effective in the future user centric network selection paradigm and operators objective function of revenue maximization, optimal resource utilization, and call blocking minimization, etc. will immensely depend on the user preferences and context. This dictates that one can translate the operators' objective as maximizing the satisfied user pool. Having accepted the fact that future telecommunication procedures will be centered around the users, in this chapter, we model the network selection using auctioning theory. We also present the realization framework for the proposed network selection approach by proposing a trusted 3^{rd} *party, IMS based architecture. We discuss realization of the proposed network selection procedures both in intra-operator and inter-operator scenarios on granule levels. This chapter also discusses issues of frequent handovers (ping-pong effect) and presents the solutions by implementing two different approaches namely; fuzzy logic based and MOS based handover reduction solutions. The proof of concept for the proposed approach is achieved by implementing different components, architecture, and carrying out measurements for various scenarios. The performance of the proposed approach is also compared to different approaches in terms of resource utilization, user satisfaction, number of handovers, and users monetary costs gain.*

3.1 Introduction

The advent of advanced wireless devices and evolution of wireless communication have significantly influenced the telecommunication business model e.g., second generation of mobile communication system turned out to be a huge success owing to its revolutionary technology, high quality speech service, and global mobility. However, the evolution from 2G to 3G could not cause significant changes in the business model. One basic reason for this unexpected slow paradigm shift was the lack of 3G new and qualitative customer services. Although realizing these causes the delay, the 3GPP attempted to incorporate some advanced services into the 3GPP architecture such as the Multimedia Broadcast and Multicast Service Center (MBMS) in combination with the IP Multimedia System (IMS). However, these smaller corrections were made without the possibility to adjust the access technology properly(41). Next comes the charming 4th Generation (4G), which is envisioned as a path to solve still unaddressed issues of the previous generations and to provide a convergence platform for a wide variety of new services, from high-quality voice to high-definition video, through high-data-rate wireless channels. Let us now converge the discussion to investigate the concrete definition of 4G. A simple one click online search provides one with hundreds of pages containing various visions of 4G definitions. Different universities, researchers, countries define the term 4G in their own perspective e.g., the European Commission (EC) envisions that 4G will ensure seamless service provisioning across a multitude of wireless systems and networks, from private to public, from indoor to wide area, and provide an optimum delivery via the most appropriate (i.e., efficient) network available. From the service point of view, it foresees that 4G will mainly be focused on personalized services (42).

In order to grab the crux of our work in this chapter, we now briefly define the 4G vision that we adhere to. We agree that 4G provides a convergence platform extended to all the network layers. In 4G, the user is located at the center of the system and the different key features defining 4G rotate around him. User personalization, user friendliness, service personalization, ubiquity are a few of the examples of such key features. This vision dictates that 4G should identify the user's functional needs and service expectations. Furthermore, the control for decision mechanisms in network or service selection scenarios should be delegated to the user terminals. We also believe that a user-centric vision will be mandatory evolution trend in future all-IP 4G networks as it represents the most efficient way to ensure an ABC service. In this vision, users will have greater control and will be able to select the *best* available access network with which they are most satisfied. This process is basically known as *network selection / interface selection / operator selection*. More on 4G can be found in (42, 43).

3.2 Motivation and Point of Interest

We now highlight and confine our discussion to the decision making problem of 4G wireless networks' stake-holder(s). In order to meet the requirements like high data rates, ubiquitous connectivity that ensures users' preferred QoS level when passing from one network technology support to another one, etc., the operators are faced with realizing seamless integration of already existing heterogeneous and upcoming network technologies. With almost all the businesses and services going online, one can expect immense increase in user demands of wireless services. In order to satisfy the increasing user demands and achieving the objective of connectivity anywhere and anytime as now commonly practiced, operators need to exploit the technologies integration concept that provide us with the widespread coverage. This in turn forces the operators or technologies to share the bandwidth resources with each other, needless to mention here that sharing criteria must meet the related constraints e.g., frequency interference constraints, etc. The details of network resource sharing can be found in Chapter 5.

This rightly dictates that the giant operators and new entrants are now interested in more flexible architectures that will enable them to keep their options open, or run parallel systems according to their spectrum and applications. For operators the most straightforward method to combat the changing telecommunication paradigm is to integrate the already deployed (or new) technologies of different characteristics and strive to increase their user pool for different extended services. Clearly, if on one hand it requires strong economic reasoning and model, on the other hand the technical feasibility of undergoing such integration is also a critical issue. The pattern of research literature addressing such problems can broadly be classified into those, presenting the numerical or analytical solutions and not going much into the architectural details e.g., (44, 45, 46), whereas the other category may be termed as the one purely concentrating on the architectural solution e.g.,(47, 48). However, we in this chapter propose an architectural solution that supports the proposed auction based network selection analytical solution.

Given the telecommunication landscape with integrated heterogeneous network access technologies, the mobility of users among the technologies has to be managed i.e., user mobility management has to be carried out. It should be noted that most of the existing mobility management solutions require agreements among the operators, who own different internetworked access networks, to be established. Intuitively in this case, the mobility management remains network-controlled. This mandates that users are unable to maintain on-going session while handing over between two access networks belonging to non-collaborating operators even if the user has subscribed to these two networks. Given this fact, one could conclude that prevailing network controlled mobility management can not cope up with envisioned user-centric approach. Consequently, the mobility management in user-centric scenario can be realized by introducing a fully user-controlled mobility management solution, where different technologies of different operators are completely independent. In this connection a number of solutions may be found in the research literature e.g., SAHARA model (49) considers the service composition across multiple providers, however SAHARA focuses on static agreements among different providers, the user dynamic inefficiency in this approach is caused by the fact that agreement have to be settled long in advance. PERIMETER on the other hand focuses on the development of services independent and portable of underlying access and transport network. Any off the shelf architectural solution e.g., broker, middleware, IMS based, etc. architectural solutions may be implemented. This further justifies the need for realizing user-centric 4G vision. Thus we can redefine the 4G vision.

Definition 3. *4G framework is defined as the framework that puts user as the focal point, values his subjective preferences, customs and habits. This vision further dictates that 4G should identify the users' functional needs and his service expectations. Users should be delegated the control of system alternate choice (network or service selection scenarios), where users select the best available alternate network operator.*

Given the definition of 4G, we now highlight the user centricity in terms of network selection. One can translate the user-centric network selection into ABC vision. The common understanding of the term *best* in the ABC takes different definitions dictated by the user preferences i.e., user defines preferences over various parameters (detailed in section 3.4) for network selection. We also define *best* in terms of satisfaction in section 3.5.1. This discerns into the following flavors of handovers:

- *QoS handover:* The reason for execution of such handovers is mainly the quality degradation of the current point of attchment or the change in user preferences over the application QoS.
- *Area handover:* Such handovers are executed as the consequence of user mobility out of the coverage of the current point of attachment.
- *Preferred alternatives:* The network selection is triggered whenever a better alternative is available (also highlighted in Remark 5).

The earlier two flavors are self explanatory. However, to illustrate on the last flavor, we consider the situation when users define their preferences over the technology types. Then in this case, the depth of network selection decision goes upto two levels namely; i) technology level - in this case, users define the preferences over network technology(ies). Obviously in this setting, the operator offers are limited to the preferred technology. ii) operator level - this level provides operator the opportunity to make use of all the available underlying network technology(ies). In this case the default assumption is that user is interested only in attaining the required QoE and has no preferences over the specific network technologies, this further leverages the operators to implement different load balancing and resource utilization operators e.g., enabling load sharing among the its different access technologies (e.g., our proposed network centric resource allocation solution detailed in Chapters 5 & 6. We also study the impact of simultaneous use of interface for load sharing from operators' perspective in this chapter.), etc.

3.3 Contribution

In this chapter, we model the QoE based user-centric network selection using auction theoretic approach. We model the interaction between operators and users in the settings, where the user takes the decision over interface(s) or operator selection. Our contribution in this chapter may be summarized as follows:

- We propose auction-based approach to model the negotiation between users and operators.
- We model the utilities of both operators and users.

- The earlier research literature in general assumes that users declare all their preferences to the operators, however in reality users may not be willing to reveal all their preferences because of the fear that operators may exploit users' preference(s) for increasing their(operators') own payoffs e.g., knowing about the users preferences over a service price, a service provider may charge more than what it really values the service. In our approach we take care of such private information of users and justify that operators' offers always contain their true value for different parameters and service charges.
- We propose the IMS based architecture that realizes the proposed user-centric approach and discuss the inter-entities interactions and protocol operations on granule level.
- We study the impact of user centric network selection over the handover frequency and propose two different handover reduction solutions i.e., fuzzy logic based and MOS based solutions.
- The proof of concept of the proposed approaches is done by implementing different components, architecture, and scenarios using OPNET network simulator.
- The performance of the proposed approaches are evaluated against various approaches in terms of resource utilization, user satisfaction, number of handovers, and users monetary costs gain.

We now present the general model for network selection, the purpose of presenting the generic network selection model is to illustrate over the basic idea and its scope both on technical and economic grounds.

3.4 Generic Network Selection Model

The network selection decision depends on the inputs from different communication entities. The information these entities contain and their objectives vary depending on the level they reside on, as depicted in Figure 3.1. The network selection decision mechanism evaluates different criteria such as service type, user device capabilities, different market segments with varying QoS requirements, network technology conditions, service provider behavior, user location, user speed, user implicit preferences, etc. Evaluation is carried out using some policies or algorithms and the outcome of decision mechanism is ideally the most suitable network service(s) that can satisfy the users' requirements. The huge number of variables involved in the

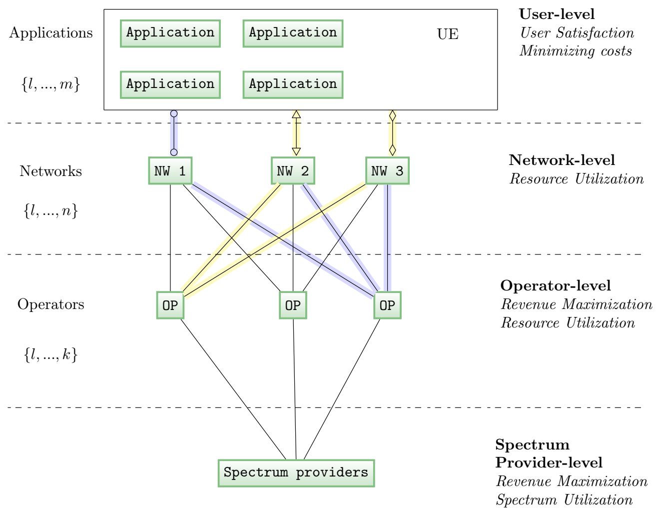


Figure 3.1: Position of different stake-holders on hierarchical layers representing telecommunication landscape - In the figure three different hierarchical levels are shown, on each level the telecommunication stake-holders are positioned. The positioning of telecommunication stake-holders is influenced by their functionalities and interdependencies. On each level the objective function of stake-holders are also listed.

decision process makes *network selection* an utterly complex problem. Table 3.1 presents a list of some major parameters that influence the network selection decision, together with their characteristics and their point of generation.

Figure 3.2 depicts the abstract view of network selection process, where the decision mechanism takes network specific, application specific, and user specific requirements as inputs. The decision mechanism is driven by the objective block, which represents the objectives of user or network operator. The decision of network selection is based on the outcome of objective block that consists of *utility function* and *cost function* blocks. Both of these functions are associated with the stake-holders (i.e., end-users and network operators, etc.). Let γ represent the set of all involved parameters in the decision making of a stakeholder. Then the utility function $u : \gamma \to \mathbb{R}$ ranks each element in the set γ such that if $u(x) \geq u(y)$ then $x \in \gamma$ is preferred to $y \in \gamma$. It is commonly assumed that the utility function is non-decreasing, however it improves with slower pace near some threshold value of considered parameter, where the player is indifferent to any value higher than the threshold value. For each input parameter, a utility curve or cost curve represents the stake holders' preferences, where the choice of utility or cost is driven by the problem formulation. Entities within objective block (of Figure 3.2) may

Table 3.1: Typical parameters influencing the network selection decision (4, 5, 6)

Parameter	**Dynamic / Static**	**Source**	**Factors Involved**
User Preferences	Static for a call duration	UE	willingness to pay, security, power, visual quality
Application Constraints	Static	UE	QoS constraints, service requirements, application requirements, application context, variety of services, adaptation ability, minimum required bandwidth, maximum loss rate and latency allowed, delay bounds, traffic specification
Reachable APs	Static in a cell	UE	
Device capabilities	Static	UE	CPU speed, memory size, display I/O, transmitted power, network interface, built-in application software platform, supported modalities, maximum object size, screen size, number of colors
Device capabilities	Dynamic	UE	Battery status, interface status
User profile and history	Static	Network	User connectivity pattern, application requests, QoS required
Network capabilities	Static	Network	Network capabilities, network equipment capabilities, access technologies capabilities, access point bandwidth, Uplink and downlink bandwidth, modulation scheme
Network Charging Model	Static for atleast a call duration	Network	Price per unit resource, price per unit time for resource usage
Potential Next AP	Static in a cell	Network	Neighboring access points
Network status	Dynamic	Network	Network used capacity, traffic characteristics, maximum saturation throughput of AP, transmitted bandwidth, bandwidth per user, delay, throughput, response time, jitter, bit error rate, burst error, loss, signal strength, available services, average number of connection, connection holding time

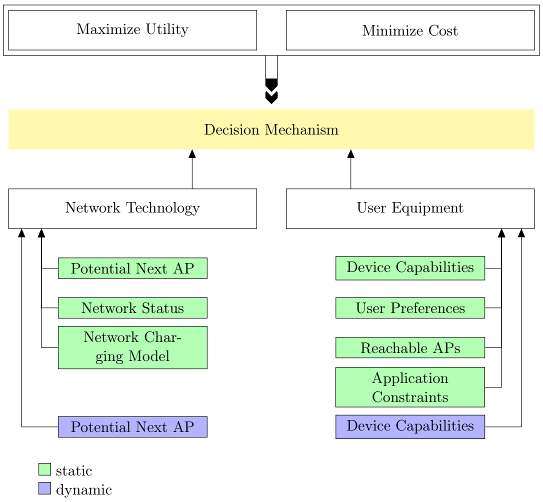


Figure 3.2: Demonstration of a typical process and related parameters for network selection - The figure indicates different types of input parameters available to the decision making block. It can also be seen that the procedures in the decision making block are influenced by inputs from objective block (i.e., the block containing objective functions like maximizing utility or minimizing costs).

have different definitions for each stakeholder. For example, the utility function for an end-user may be defined in terms of available bandwidth, received signal strength, degree of reliability, throughput; and the cost function in terms of bit error rate, transfer delay, service charges, transfer latency, etc. For the sake of simplicity, a common term *payoff* is used interchangeably for utility and cost functions, which refers to the satisfaction level of stake-holders.

There has been significant research activity on decision mechanisms for network selection based on both end users' and network operators' utility / cost functions. We now present a comprehensive overview of both perspectives studied in the literature using various approaches including game-theoretic approaches, etc. We categorize the approaches into the following categories: i) user-based network selection, ii) user-centric operator based network selection, iii) impact of pricing in network selection, and iv) Miscellaneous approaches.

3.5 Background and Literature Review

In this section, we present the basics of user-centric network selection. This section also focus on presenting the literature review in this direction

3.5.1 User-Based Network Selection (Interface Selection)

Modern mobile communication devices are equipped with multiple wireless network interfaces and hence can be associated to different network technologies, potentially belonging to different network operators. The decision mechanism on the UE gets information on relevant factors as inputs, including user preference, application specific requirements, network conditions, price offers, etc. Upon receiving the information, the decision entity employs various decision making techniques resulting in an interface selection. Typically the UE selects a single network interface for connectivity of the device, which is used by all user applications. However, with increased multitasking capabilities of mobile terminals, the interface selection can be done on a per-application basis; i.e. the interface selection decision associates each application running on the UE separately to a suitable access technology or even multiple access technologies.

In its most generic sense, *user-centric* view considers that the users are free from subscription to any one operator and can instead dynamically choose the most suitable transport infrastructure from the available network providers for their terminal and application requirements (50). In this approach the decision of interface selection is delegated to the UE enabling end-users to exploit the best available characteristics of different network technologies and network providers, with the objective of increased satisfaction. The generic term *satisfaction* can be interpreted in different ways, where a natural interpretation would be obtaining a high QoS for the lowest price. In order to more accurately express the user experience in telecommunications, the term QoS has been extended to include more subjective and application-specific measures beyond traditional technical parameters, giving rise to the QoE concept. QoE reflects the collective effect of service performances that determines the degree of satisfaction of the end-user e.g., what user really perceives in terms of usability, accessibility, retainability and integrity of the service. The subjective quality perceived by the user has to be linked to the objective (as detailed in Chapter 2, measurable quality, which is expressed in application and network performance parameters resulting in QoE. Feedback between these entities is a prerequisite for covering the user's perception of quality. Non-technical parameters necessary for evaluating QoE usually require subjective user evaluations that are hard to obtain. Existing methods include utilizing a Graphical User Interface (GUI) for user feedback (51) (52), Analytical Hierarchy Process(AHP) (53), Pseudo-Subjective Quality Assessment(PSQA) (54), and learning algorithms to reduce the user-system interaction (55).

Since user requirements span over different parameters of user preferences and application specific requirements, the simplest and most commonly used methodology to get an overall user policy is a weighted sum of all parameters (56, 57). Letting l denote the parameter, the payoff associated to the selection of an available access network may generally be defined as

$$Payoff(network) = \sum_{l \in L} (weight_{parameter(l)} \times g_{parameter(l)}(.)), \tag{3.1}$$

where a careful choice of the cost / utility function $g_{parameter(i)}(.)$ is crucial (58). However, we deviate from this form of user satisfaction function and propose an hybrid multiplicative and additive approach (refer to Chapter 2).

3.5.1.1 Game-theoretical Interface Selection Example

To illustrate the fundamental concepts of game-theory in network selection, we consider a simple two-player game between a user and a network provider. It is assumed that the user is already associated to a provider and her utility is translated as her satisfaction from the current service of current provider. Similarly the network provider has a number of users associated to it and it has some current revenue V prior to game play with player in question, where revenue is the natural utility of the network provider.

Non-Cooperative Game Let $\Gamma = (P, \mathcal{S}, U)$ represent the game, where $P = \{$network provider, end-user$\}$ denotes the set of players, $\mathcal{S}$ represents the strategy set of players, and U is the set of player utilities. Strategy set of network operator o is $S_o = \{$high QoS / price offer $\bar{\pi}$, low QoS / price offer $\underline{\pi}\}$ and user j has the strategy set $S_j = \{$stay connected with current operator (st), Handover to network operator $\{(ho)\}$.

Let $\nu_{j,c}$, $(\nu_{j,e} - \pi_j)$ be the current and estimated valuation of users from the current operator and the offered service from target operator respectively, where the valuation is driven by the satisfaction of users from service. Moreover, let ci_o represent the incurring cost by the operator on extending the QoS to users, π_j the payment by user for the service, and $R_o = V + (\pi_j - ci_o)$ the expected revenue after the user hands over to the network, where $(\pi_j - ci_o)$ denotes the expected increase in the revenue of the operator. The utility functions $U_j : S_j \times S_{-j} \rightarrow \Re$ for both players are different and conflicting as given in Table 3.2. The solution to this problem may be derived by various methods such as strictly / weakly dominant strategies. The solution concept that we adopt in this example utilizes Nash Equilibrium using Best Response Function.

Case-1: Assume that the user is indifferent to both offers of the operator (low or high QoS) and that $\nu_{j,e} - \bar{\pi}_j > \nu_{j,c}, \nu_{j,e} - \underline{\pi}_j > \nu_{j,c}$, which dictates that user is always motivated to handover, as her utility increases following this strategy. Then the best response to this strategy of operator-1 is offer 1 when $(\bar{\pi}_j - \bar{ci}_o) > (\underline{\pi}_j - \underline{ci}_o)$, and offer-2 when $(\bar{\pi}_j - \bar{ci}_o) < (\underline{\pi}_j - \underline{ci}_o)$. Since these strategies are mutually best responses to each other, then players have no reason to deviate from given strategy. The efficiency of the solution may be evaluated using the Pareto-optimality concept.

Case-2: Now consider that $(\nu_{j,e} - \bar{\pi}_j) < \nu_{j,c}$ in operator first offer $(\bar{\pi})$, and that the expected utility of user is more than her current utility i.e., $(\nu_{j,e} - \underline{\pi}_j) > \nu_{j,c}$, in the second offer $(i.e., \underline{\pi})$. In this case the solution of game turns out to be offer-2 $(i.e., \underline{\pi})$.

$user \setminus NP$	$\bar{\pi}$	$\underline{\pi}$
ho	$\nu_{j,e} - \bar{\pi}$, V $+(\bar{\pi} - \bar{ci}) \rightarrow$ ②	① $\leftarrow \nu_{j,c} - \underline{\pi}$, V$+(\underline{\pi} - \underline{ci})$
st	$\uparrow \nu_{j,c}$, V $\leftrightarrow$	$\leftrightarrow \nu_{j,c}$, V $\uparrow$

Table 3.2: A two player example - The matrix representing the strategies of both the players, their respective utilities, and the Nash Equilibrium convergence solution (the solution can be tracked with the help of arrows' directions.)

Cooperative Game It is very difficult to achieve cooperative benefit if it is assumed that players are rational and pursue their self interests only. The dilemma of achieving cooperation based on selfishness is famously illustrated by the Prisoners' Dilemma Game. In such two-person cooperative games, the players' utilities may be translated in four types i) temptation, ii) reward (cooperating), iii) sucker, and iv) punishment. However, in the above game to illustrate cooperative nature of users, let $(\nu_{j,e} - \underline{\pi}_j) = \nu_{j,c}$ in the second offer $(\underline{\pi}_o)$ of operator and also $(\underline{\pi}_j - \underline{ci}_o) > (\bar{\pi}_j - \bar{ci}_o)$. On the other hand, in the the first offer $(\bar{\pi})$ assume that $(\nu_{j,e} - \bar{\pi}_j) > \nu_{j,c}$. Then in this case user can threaten operator to play $\bar{\pi}$. If operator doesn't agree to cooperate, the threat is carried out, and in this case if user plays stay connected strategy, the operator's expected utility $V + (\underline{\pi}_j - \underline{ci}_o)$ reduces to V, therefore cooperative behavior here guarantees better utilities $(\nu_{j,e} - \bar{\pi}_j)$, $V + (\bar{\pi}_j - \bar{ci}_o)$ and reduces risk of utility loss.

3.5.1.2 Non-cooperative Interface Selection

Non-cooperative game theory studies the strategic choices resulting from the interactions among competing players, where each player chooses its strategy independently for improving its own utility or reducing its costs.

Definition 4. *A general non-cooperative game can be modeled as follows. Let* $\Gamma = [N, S_i, U_i]$ *represent a game where* $N = \{1, \ldots, N\}$ *represents the set of players / users,* S_i *the strategy* *set available to each user i, and U_i the utility function of user i. Each user bases its strategy on maximizing its own utility i.e.,*

$$max_{s_i \in S_i} U_i \, for \, N = \{1, \ldots, n\}. \tag{3.2}$$

There exist two main solution concepts for non-cooperative games, namely *Nash Equilibrium* and *Pareto Optimality*, as defined next.

Definition 5. Nash Equilibrium – *A pure Nash equilibrium of the game $\Gamma = [N, S_i, U_i]$ is a strategy profile $s^* \in S_i$ such that for every player $i \in N$ there exists:*

$$U_i(s^*_{-i}, s^*_i) \geq U_i(s^*_{-i}, s_i) \, for \, all \, s_i \in S_i, \tag{3.3}$$

where $s_{-i} = (s_j)_{j \in N \setminus \{i\}}$ denotes the strategy profiles of all players except player i. This indicates that there exists no strategy $s_i \in S_i$ of player i that is preferred over his Nash strategy s^*_i irrespective of the strategy of all other players $j \in N \setminus \{i\}$. The strategy profile $s^* = (s_1, \ldots, s_n)$ is a Nash equilibrium when this holds for every player $i \in N$.

Definition 6. Pareto Optimality *is used to assess the efficiency of equilibrium point. A strategy profile s^* is Pareto-optimal if there exists no other strategy profile s' that is Pareto-superior to s^*. A strategy s' is Pareto-superior to strategy s if for any player i: $u_i(s'_i, s'_{-i} \geq u_i(s_i, s_{-i})$. In other words, the strategy profile s' is Pareto-superior to the strategy profile s, if the payoff of a player i can be increased by changing from s to s' without decreasing the payoff of other players.*

As noted earlier, players (i.e., the users) try to form a strategy to maximize their payoffs. This results in an important requirement for the appropriate choice of a utility / cost function. The choice of utility / cost function influences the game to a great extent mainly in terms of strategy selection by the players. In the domain of network selection problem, researchers have contributed various utility / cost functions, which affect end users strategies to select among available access networks.

One such framework is used in (59) where a *non-cooperative game* is formulated among end-users, who strive to minimize the cost function. In this scenario a user plays in a congested WLAN-covered service area, and to maximize his bandwidth he has the choice to physically traverse a distance to get associated with a less congested access point. The congestion in this case refers to Access Point (AP) load. One of the approaches to model the *payoff function* in this case is maximization of user received bandwidth. A user is satisfied if i) she gets associated to an AP that has less number of already associated users, and ii) the distance to traverse in order to use the target AP is minimum. To capture both these desired characteristics authors model the cost function as

$$Cost_{jw} = \tilde{\alpha} x_j + Di_{jw}, \tag{3.4}$$

where $Cost_{jw}$ is the cost assigned by user j to AP w, x_j is the number of already associated users, Di_{jw} is the distance to be traversed to use AP w and $\tilde{\alpha}$ is the relative weight assigned by the user to load and distance with the value between $\{0, \infty\}$. Here $\tilde{\alpha}$ captures user preference relationship between distance and QoS – a higher value of $\tilde{\alpha}$ shows greater concern of user toward target AP load. A myopic algorithm for access selection is suggested, which leads to Nash equilibrium for a simple user exit model (where the users are assumed to exit the system shortly after each other, almost simultaneously). However, the solution is no more stable with more realistic assumptions i.e., when users generate varying load and exit the system dynamically. In this case the gain that user attains by unilateral change of strategy is proportional to the diversity of users. Thus a stable system is more likely to result with lower user diversity. The authors further study interference based cost function, additive interference rate cost function, and multiplicative interference based cost function by formulating and solving the problem as congestion games.

Remark 3. *Users' behavior of getting associated with less interfered AP specifically in interference limited network technologies e.g., CDMA, WiFi, etc., can be modeled using* congestion games*, which belong to class of non-cooperative games (60). Such games are well suited to model resource competition where resulting payoff is a function of the level of congestion. The generalized form of congestion games is given by* $\Gamma = (N, R, (\sigma_i)_{i \in N}, (g_r)_{r \in R})$*, where* $N = \{1, 2, \ldots, N\}$ *denotes a set of users,* $R = \{1, 2, \ldots, R\}$ *a set of resources,* $\sigma_i \subset 2^R$ *the strategy space for player* i*, and* $g_r : N \to Z$ *a payoff (cost) function associated with resource* r*. Authors in (61) model interface selection problem under three different cost functions using congestion games, where efficiency of the Nash equilibrium solution is analyzed for each of these cost function.*

The assumption of users' almost simultaneous exit pattern identified earlier in (59) refers to another issue in interface selection. In scenarios such as passengers on a train or bus moving out of the coverage area of current point of attachment, end users tend to handover simultaneously. Simultaneous rational decision of most users converge, for example, selection of the operator that has the least load. However, the selected operator / network may no longer remain as the suitable option after the group handover of many users is executed. Such problems fit well in the congestion games branch of game theory. The European Union project C-CAST specifically addresses these issues in the context of mobile multimedia multicasting.

Interface selection in the case of *group handover* is discussed in (62), in which end-users' satisfaction is translated to minimizing the transfer latency of the application data i.e., a mobile user selects the network that has minimum transfer latency. A network is characterized by its capacity and transfer latency cost, where transfer latency in turn is a function of traffic load and available capacity of the network. Two types of latency functions are considered namely; i) linear latency function and ii) latency function based on M/M/1 queuing model.

The *interface selection* problem is formulated as K-P model of the congestion games and three algorithms are proposed in (62) for *network selection*: i) Network selection based on Nash equilibrium strategy ii) Network selection with random delay iii) Network selection with random delay considering handover latency. The algorithm based on the Nash equilibrium requires unrealistic assumptions e.g., end users have the information about all networks and traffic loads of other users, but is used as a reference to compare other proposed algorithms. The algorithms with *random delay* and *random delay with handover latency* are carry out the network selection in more realistic scenarios.

User-centric interface selection mainly focuses on the local objective of user satisfaction and usually disregards the global objective of congestion control and optimum network resource utilization. Unlike such approaches described so far in this section, Niyato et al. discuss the user-driven load balancing approach while network selection is performed on the user side (63). Competition among groups of users (groups formed on the basis of service class) in different service areas covered by heterogeneous wireless networks is modeled using evolutionary and non-cooperative games. The *evolution equilibria solution* based on the replicator dynamics is defined, which is the stable set of fixed points of the replicator dynamics. Evolution equilibria ensures that all users within the same group receive the same payoffs. The evolution game for network selection is implemented using two algorithms, population evaluation, and reinforcement learning. Evolutionary equilibria solutions are compared with the Nash equilibrium obtained from the conventional non-cooperative games. The payoff of users within evolutionary game is determined by their net utilities.

3.5.1.3 Cooperative Interface Selection

Cooperative game theory provides analytical tools to study the behavior of rational players when they cooperate. The main branch of cooperative games describes the formation of cooperating groups of players, referred to as coalitions, which can strengthen players' position in a game. There exist various solution concepts for coalition games including *Core*, $\tau-$value, *nucleolus* and *Shapley value* (64).

Definition 7. *Coalition games consists of a set of players, a set of strategies for each coalition, and preferences. Efficiency of a coalition is quantified by a characteristic function. More formally, the coalition games are of the form (N, v), where $N = \{1, 2, \ldots, n\}$ is the set of players and $v : 2^N \to \mathbb{R}$ is the characteristic function that assigns each coalition of players $S \subseteq N$ a worth $\tilde{v}(S)$. It is assumed that $\tilde{v}(\emptyset) = 0$ and $\tilde{v}(S)$ can be defined as the payoff that each member of coalition S can obtain for themselves if they coordinate their actions, independent of the actions taken by the players outside of the coalition S (65). The strategy set of player $i \in N$ is represented by $S_i = \{T \mid T \subset N \backslash i\}$, where a particular strategy $s_i \in S_i$ represents the set of players with whom player i would like to form coalition.*

The total utility represented by the characteristic function that coalition achieves can be divided among the players of coalition and such games are called *transferrable utility games*. The preference of users is modeled by their utility functions, similar to the non-cooperative case. The outcome of the game consists of a partition of the set of players into groups. To further elaborate this, let us consider an example scenario, where the network technologies $w \in N$ cooperate with each other to satisfy the user request by assigning predefined bandwidth (detailed later in this section). Network technologies form coalition $S \subseteq N$, where the payoff of coalition is given by characteristic function $\tilde{\nu}$. Let the amount of requested bandwidth received by each network technology is given by a payoff vector $x \in \Re$, which is an imputation for the game if it is efficient and individually rational i.e., i) $\sum\limits_{i \in N} x_i = \tilde{\nu}(N)$ and ii) $x_i \geq \tilde{\nu}(i)$ $\forall i \in N$.

To narrow down the imputations and attain stable solution we illustrate the concept of *core*. The core $Cr(\tilde{\nu})$ of a game is the set $\{x = [x_1, \ldots, x_n] | \sum\limits_{i \in S} x_i \geq \tilde{\nu}(S), \forall S \in 2^N\}$. There are situations when the core is empty. Shapley value and the $\tau-$value are one-point solution concepts. Let us investigate the Shapley value concept for the aforementioned problem. The Shapley value associates to each game one payoff vector in $\Re^n$ and it is denoted by $\phi(\tilde{\nu})$ of a game is the average of the marginal vectors of the game i.e.,

$$\phi_i(\tilde{\nu}) = \sum_{S: i \notin S} \frac{|S|!(n - 1 - |S|)!}{n!} (\tilde{\nu}(S \cup i) - \tilde{\nu}(S)) \tag{3.5}$$

Here S indicates the number of elements in the set S. The outcome of above allocates different amount requests to available network technologies, which should be efficient solution.

A cooperative game is usually modeled as a two period structure. Players must first decide whether or not to join coalition, which is done by pairwise *bargaining*. Bargaining problems refer to the negotiation process, modeled using game theory tools, to resolve the conflict that occurs when there are more than one course of actions for all players in a situation. Players involved in the games may try to resolve the conflict by committing themselves voluntarily to a course of action that is beneficial to all of them.

Bargaining problem is modeled as a pair $(F, \tilde{d})$, where F represents the set of all feasible utility pairs and $\tilde{d}$ represents the *disagreement point*. By definition, players do not participate in a coalition if the utility that they receive is less than the specified disagreement point. Typical bargaining solutions include Nash bargaining solutions, Kalai-Smorodinsky bargaining solutions (KSBS), modified Thomson rule, etc. All such solutions have to satisfy the axioms of i) individual rationality, ii) Pareto optimality, iii) independence of irrelevant alternative / individual monotonicity, and iv) symmetry.

The most common form of a cooperative relationship in the user-based network selection is network-user cooperation. Recall that users have the objective to increase their satisfaction level by paying less, and network providers strive to increase their revenues, which seemingly indicate conflicting interests for the two entities. On the one hand, it is clear that a user-centric decision alone may not take into account optimal resource utilization or congestion control at the network level, which are key issues for the network providers' objectives. However, on the other hand, when the number of users in a service area increases, the satisfaction level of each individual user decreases. Therefore the users would be willing to cooperate with the network operators, who in turn are willing to cooperate with users for better utilization of their resources, resulting in a mutual increase in their payoffs (66).

Direct cooperation among users for interface selection is also possible, though they are generally studied within the scope ad hoc networking and falls beyond the scope of this text. In general, most of the cooperative network selection approaches fall into the network-based decision domain.

3.5.2 User-Centric Operator-based Network Selection

Next generation networks and the $4G$ vision evolve around user priorities as mentioned earlier, while the objectives of efficient resource allocation and congestion control can best be achieved when the network selection decision is delegated to network operators. If user policies are taken as a priority but the decision is still made on the network operator side, the two objectives of better resource management and higher user satisfaction may be simultaneously achieved. This sections covers game theoretic approaches for network selection that place the decision entity on the operator side while taking user preferences or inputs into account.

Cesana et al. (67) capture the interface selection resource distribution by modeling a *bi-level stage game*, where the resource distribution game is dependent on the interface selection game. At the interface selection level a non-cooperative game is played among end users. Since the reference scenario is a *homogeneous networks scenario* (only WiFi APs), the cost function of the player is defined as the function of interference perceived by users, which in turn is defined as the total number of end users covered by the same access network covering the player j and is given by $\{n_j(S_u)\}_{j \in U}$. The game formulated at the user level is defined as

$$\Gamma_u = (U, N, S_u, \{n_j(S_u)\}_{j \in U}), \tag{3.6}$$

where U represents the users, N access networks, and S_u the strategy set of users that include the reachable access point.

Another non-cooperative game at network level is played among network technologies for resource distribution. Strategy set includes the set of frequencies which can be chosen by any network w and payoff $R_w(S_w, \Gamma_u)$[1] of network w, which is defined as the number of end users that decide to associate to the access network w when it plays the strategy profile S_w. In this *bi-level stage game* the lower level game leads to Nash equilibria of the network selection with the frequency assignment as a parameter, whereas the upper-level game seeks to allocate the frequencies among access networks given the responses of the end users to these assignments.

$$\Gamma = (W, S_w, \{R_w(S_w, \Gamma_u\}_{w \in W})) \tag{3.7}$$

Numeric results show that despite of the rational behavior of players, this game finds equilibria condition where both end users and networks tend to be fair with respect to the other players.

Authors in (68, 69, 70) evaluate the preferred network by using different mathematical modeling techniques. Although not explicitly mentioned in (68), the format of formulated game among network providers belong to congestion games, expressed as $\Gamma = (\mathcal{O}, \tilde{R}, S_o, U_o)$, where the player set $\mathcal{O}$ represents network operators, resource $\tilde{R}$ represents the requests from users, S_o represents the strategy set of players i.e., for acquiring resources, and U_o is the pay-off value tied to a user assigned value or alternatively to the network technology evaluation process of users. A user evaluates available network technologies for attainable *application*

[1] R_w: For the sake of simplicity, we generalize network payoff as revenue

QoS, *pricing*, etc. Different QoS parameters are assigned weights using AHP, which refer to the priority of parameters for service / applications. Given the quantitative relationship among different QoS evaluations (obtained by AHP), Grey Relational Analysis (GRA) (71) indicates the optimal network for specific application, where the network with higher Grey Relational Coefficient (GRC) value is preferred to the one with a smaller GRC value. Dynamic status of network technologies in terms of available capacity is considered and input as a parameter to the decision mechanism, which computes the preferred network w^* as

$$w^* = GRC \frac{\text{Available Bandwidth}}{\text{Required Bandwidth}} \tag{3.8}$$

Therefore each service request is accompanied by GRC values assigned to different available network technologies. The stability and efficiency of the solution is not discussed.

Authors in (69, 70) formulate the call admission control in a similar way using non-cooperative games played among operators where common resources are the service requests. Game output is decision of the subset of service requests that is admitted to the network. Players, resource, payoff, and strategy set in this game formulation are similar to the one discussed in (68). The sequence of process is: i) Providers separately offer access to service request with some predicted value of different QoS parameters, ii) Users send service request with associated preference value of available networks to the *4G system*, which in turn is translated into network technology payoffs, iii) Network technologies select the service request that increases their payoff. As different from (68), the suitability of a network technology is computed by dividing the possible user service requests into two broad categories namely RT and NRT services. User satisfaction is translated in time (in terms of delay and jitter) and observed packet loss. Since NRT services are not sensitive to delays, users' preference over delay can be a constraint in such a case, whereas in RT traffic application required delay is a constraint. Assuming that users can not perceive packet losses until they are higher than some threshold, the utility function is given as the function of delay and jitter. Network predicted parameter values of delay and jitter are mapped to the utility of users, who accordingly assign preference to available networks. Utility function of user in turn decides the payoff of network technology, where the preference value assigned to any particular network motivates the networks to compete for service request to increase their payoffs.

Chen et al. (72) introduce the concept of *arbitration probability* to evaluate the available technologies and compute the preferred technology. It is used to model the utility function and reflects the level of willingness that a user wants to use the service of any available network.

The attributes of arbitration probability include i) satisfaction level of users, ii) relative link quality, iii) service pricing. User satisfaction level is modeled using *sigmoid function*. Users select the network with the highest arbitration probability value. A non-cooperative game $\Gamma = [W, \mathcal{S}_w, U(.)]$ is modeled to reflect the competition among available networks. Network technologies are players, $\mathcal{S}_w$ is the strategy set of network w. Utility function that represents the profit that network may earn by providing resource to user is modeled using arbitration probability and is given by $U_w = n_w \pi_w(r_w) A_w(r)$, where n_w is the maximum number of users that network can accommodate at the same time, π_w is the price charged by network w for allocating bandwidth r to request and $A_w(r)$ represents the arbitration probability value assigned by user against the offer (containing amount of bandwidth, link quality and pricing information) of network w. The unique Nash equilibrium is computed as the solution of the modeled game.

The increasingly dynamic nature of the telecommunications scene is expected to go beyond the technical domain and also cover business models and socioeconomic aspects of telecommunications. For example, PERIMETER (73), an FP7 (Framework Program 7) project funded by the European Union, aims to establish a new user-centric paradigm in telecommunications where users can switch among different operators and different technologies in real time without being bound to any contractual agreements. Also in (74) and (70) the term *4G system* is used to refer to a scenario where a third party is responsible for collecting user generated service requests and distributing them among available networks technologies. This entity should also ensure that the network operator delivers the agreed level of service quality to user and take care of billing and security issues. There are many challenges, both technical and socioeconomic, that need to be addressed for this vision to come true, such as the need for a standardized view of QoE among all stakeholders that should act as a common performance and valuation criterion. Pricing schemes also become very important in such a dynamic environment, which is addressed to some extent by researchers, as listed in section 3.5.3. Further research is needed in the direction of mechanism design for such independent entities or alternative solutions for inter-operator arbitration in future dynamic networks.

In Table 3.3, we summarize the some of the utility formulation available in the research literature in user-centric scenarios.

Table 3.3: Typical parameters influencing the network selection decision (4, 5, 6)

Ref.	Player(s)	Payoff	Strategies
(61)	Users	Minimizing user selection cost	APs in the region
(66)	Users	Minimizing the cost, whereas cost function is dictated by increasing number of users and increasing distance to be traversed to use AP. Cost function should be defined.	APs, moving / not moving
(75)	User groups	Users satisfaction, based on his utility which is the function of allocated bandwidth and price per unit.	APs
(70)	Network and Users	Users Satisfaction	RANs
(76)	Providers & customers	the function of customers' received rate, power consumption. Payoff of provider is difference between revenue and costs.	Joint action set of provider and customer.
(77)	Users and Networks	User : maximize the perceived QoS. Network: maximize the mobile users in user pool.	User: Set of available networks Network: Choosing different frequency channels.

3.5.3 Impact of Pricing on Network Selection

Although so far the focus of the chapter remained on problem of network selection mainly based on technical parameters and objectives, economic models also play a crucial role in the decision of both users and network operators. Integrating pricing mechanisms into technical aspects of network selection helps capturing the problem more realistically. Therefore we briefly visit pricing issues in this section in a compact tabular form.

Some of the commonly used pricing schemes include i) Flat-rate pricing – services are offered for a fixed period of time with a fixed price irrespective of the amount of service used, ii) Usage base pricing – users are charged for the amount of service they use, iii) Static pricing - pricing is known prior to service usage, iv) Dynamic pricing - pricing is tuned during service consumption

This section concentrates on dynamic pricing owing to its realistic applicability to next generation user-centric wireless networks, where optimum resource utilization and congestion control are also key issues. Different game-theoretic approaches in this direction are categorized as *Leader-Follower*, *Multi-stage*, and *Auction-based* methods, and are summarized in following table. In *Leader-follower (Stackelberg)* games (78), the dominant firm, the leader, maximizes its profit subject to all other firms, the followers, being in a competitive equilibrium.

Leader Follower Pricing Schemes		
Ref:	**Utility**	**Details**
(79)	**Leader**: Service Provider – $U_l(\pi, r)$: Leader sets price π for resource r **Followers**: Users – $U_f(\pi, r)$: Followers compute their demand function depending on price π.	Addresses Internet pricing. Takes maximal acceptable response time as QoS metric of user service. It is shown that performance of leader-follower approach does not lie on Pareto boundary. Bargaining solution dictating cooperation among players is used. It is concluded that players are better off when they cooperate. Approach is extended to two ISP cases.
(80)	**Leader**: WiMAX **Followers**: WiFi (APs) Utility of WiFi k is the difference of revenue earned from its users and cost paid to WiMAX base station: $U_k(R_k - C_k)$ Demand function of WiFi k is $b_j(\pi_k) = C_j - d_j\pi_k$, where $b_j(\pi_k)$ is required bandwidth by j for announced price π_k.	WiMAX uses dynamic pricing scheme to extend services to WiFi owing to elastic nature of applications on WiFi user nodes. WiMAX charges its subscriber stations with fixed prices. Payoff of both WiMAX and WiFi depends on demand functions and accordingly leader sets the prices.
(81)	**Leader**: Network **Followers**: Users Utility of network n is the revenue earned by payment λ_i of all users $i \in N$, $U_n = \sum_{i=1}^{N} \lambda_i T_i$, Utility of user i is the average number of bits transmitted correctly per joule battery power $U_i = \frac{T_i}{p_i}$.	Network decides unit price of resource and accordingly users decide the transmitted power. A joint user and network centric problem is formulated using non-cooperative games among users, where users adjust their powers in a distributed fashion to maximize their utilities. Unique NE in user-centric case is found and solution for revenue maximization is found by multi-dimensional search on unit prices of each user.
Multi-stage Pricing Schemes		
Ref:	**Utility**	**Details**

(82)	Three levels of market vision. Utility of spectrum provider for bandwidth allocation to service provider 1 (b_1) and provider 2 (b_2) is given by: $u_i(b_1, b_2) = \theta_i b_i P(\theta_1 b_1 + \theta_2 b_2) - b_i C(b_1 + b_2)$, where θ_i represents the provider i's spectrum usage efficiency factor.	The three different levels of market include i) spectrum level ii) service provider level and iii) user level. Service providers sitting in the middle layer compete with each other on one hand for spectrum share from spectrum provider and on the other hand tend to increase satisfied user pool. Such multiple competitions are modeled using multi-stage games. In first stage service providers decide the amount of bandwidth to be bought from spectrum provider. In the second stage service providers produce services and set prices. Game is solved using backward induction. Existence of Nash Equilibrium for two-stage game is proven.
(83)	Users' utility function is a function of client's intended session length K and the price paid for duration of service used; $f(t, k) - \sum_{i=1}^{t} P_i$. Base stations' utility function is given by $\sum_{i=1}^{t} P_i$.	The interaction between a base station and paying client is formulated using a simple two-player game model. At the beginning of each game AP selects the price and users have options to connect by accepting the price or reject. Players choose between two service providers for i) web-browsing ii) file transfer. Browsing formulation leads to a constant price Nash Equilibrium but the outcome is inefficient for file transfer users.
(84)	Utility of service provider i is the difference between revenue earned from service and price paid for network infrastructure: $U_i(\pi, f) = \pi_i D_i(\pi, f) - R_i(f_i - d_i)$. Cost function is given by $C_i = R_i(\pi, f_i, d_i)$. Aggregated demand function of i is $d_i = D_i(\pi_i, f)$, where($\pi = payment$, $R_i = revenue$).	In this service providers and network infrastructure owner are decoupled. Competition among service providers is modeled using a non-cooperative game. Service demand of the service provider is assumed to be a linear function of vector of prices and QoS of all providers. Two types of games are modeled: i) keeping QoS of all providers fixed and allowing service prices to vary, ii) both QoS and pricing are set by providers. Existence of Nash equilibrium is proven analytically under some assumptions.
Leader Follower Pricing Schemes		
Ref:	**Utility**	**Details**
(85)	Negotiation of QoS for the required service with registered networks is considered. A decision of selecting any suitable network in this connection is consequence of a trade-off between price and QoS.	It provides offered resources at different prices in a dynamic market. Offered price is one of the factors that motivate users to select the service that best suits their preferences in terms of price and reputation of providers. Network resources are sold using a variant of first-price sealed bid auctioning format. Simulation results exhibit that two-operator case admits equilibrium and offer the same price, whereas any additional operator causes decrease in market prices.

(86)	Sellers utility = Revenue: $n\int_{v^*}^{\bar{v}}(vF'(v)+F(v)-1)p(v)dv$ v^* is reserve price, n is number of bidders and $\bar{v}$ is maximum bidders value, $p(v)$ is probability of a bidder to be one of the auction winners, $F(v)\in\{0,1\}$.	Discusses the effect of pricing on congestion and traffic management. The auction is carried out on calls arriving at $GPRS$ based networks. In case delay is observed auction-based pricing mechanism is invoked to admit the data calls. Multi-unit Vickery auction is used and auctions are carried out for new calls only. GPRS base station has reserved price v_o that enables it to withdraw auction from bid not covering the operating cost. Reserve price varies in congestion situations v_c, such that $v_c \geq v_o$. Correlation between mean system delay and congestion reservation price is studied.
(87)	User $j's$ utility when connected to base station a_j is modeled as the received QoS and measures the performance in bits per joule.	Considers distributed power control in multi-cell wireless data system. Base station assignment is based on maximum receive signal strength (MRSS) and maximum signal to interference ratio (MSIR) are discussed. Both models are analyzed in the presence of pricing. Two pricing models are introduced as local pricing and global pricing. Nash equilibrium of both models are given.

3.6 Auction Based Network Selection

In this section, we discuss the proposed auction-based network selection approach. The focus of this chapter is confined to three of four hierarchical levels. These levels are depicted in Fig 3.3, which is a variant of Fig 3.1.

The technical and economic evolution of user-centric paradigm will help transition from a monopolist technology driven environment to a multi-player, service-oriented, user-satisfaction driven environment. This dictates that telecommunication will be shaped as an aggregation of disintegrated components, where network access is decoupled from the service or content provisioning. Intuitively, one may envision various new relationships between the existing telecommunication players and the new entrants. However, the scope of this chapter is limited to the relationships that are required for realizing telecommunication paradigm which is based on fact that *users will have short term contracts with network access providers*. We discuss the relationship between service providers, network access providers, and the users in the user-centric settings. Obviously, the relationships are based on the nature of interaction among the involved players e.g., a user interacts with service provider and acquires the network access service by herself (88) or a service provider (acting as a third party) acquires the transport services for extending services to the users. However, when considering the interaction between user and access network provider as the main interaction, one business model dimension may be that access providers may decide to form a joint venture and let a third party handle the offer extensions to the users on their behalf. In this case, the operators rely on a trusted third party to mediate the network selection operations. On the similar lines, the extensively researched approach of spectrum brokers may also be treated as a third party spectrum allocation solution. The crux of the discussion so far establishes a point that in all the scenarios, the user-centric paradigm will in someway involve the third party entity. The existence of third party is also justified by the evolved service payment methods, where users do not necessarily have the database with all the available network access providers (89) and instead pay for services to the third party, which is then shared between the service providers, network access providers, etc. Third party solution turns out be a potential one for assigning default access network connectivity to the (short term contractual agreement) users. In this chapter, we present a generic third party based architectural solution that may be adapted to any specific case scenario. The choice of this solution is also driven by the proposed auction based network selection approach.

As evident in Fig 3.3, we propose a trusted third party *Communication Service Operator (CSO)* in the architecture. We assume that CSO is responsible for the following functions; i) Authentication, Authorization, Accounting, ii) Negotiate with users on behalf of operators for their service requests and decide on resource allocation. iii) Handle handover triggers to ensure the uninterrupted delivery of service to the users. However, it should be noted that the interaction among entities and the requirements are scenario specific and may be adapted accordingly. The proposed user-centric network selection approach is basically a dual stage decision process as depicted in Fig 3.3. The architecture integrates a number of systems including network operators, network access technologies, and number of users in abstract coverage areas. We consider a coverage region covered by various Radio Access Networks (RAN) owned by different operators. The RANs are characterized by their heterogeneous characteristics. The coverage region is divided into smaller coverage areas, where the smaller coverage area may be defined as the geographical region which is covered by element(s) from the set of RANs. An area may be covered by a single RAN or multiple RANs belonging to a single operator or multiple operators. Given the user-centric network selection paradigm, users do not have long term contractual agreements with any operator and instead can connect to any technology belonging to any operator. Users generate requests for different application classes in abstract coverage areas. Very similar to the auction procedures, the negotiations between the

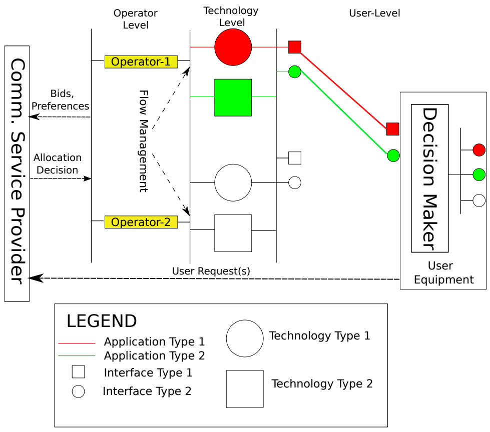


Figure 3.3: Abstract view of proposed 3^{rd} party based network selection architecture - The figure is a variant of Fig 3.1, which details the positions of involved stakeholders and their interactions. In addition to pictorially representing the interaction, the figure also highlights the position of enforcing the proposed flow management solution in case of simultaneous use of interfaces for any application.

users and operators are arbitrated and settled down by the trusted their 3^{rd} party (CSO). Service requests are classified mainly by their required bandwidths and associate QoS attributes. However, in the proposed model the required bandwidth, QoS attributes, and user service cost preferences are translated into user estimated MOS values that we get from the utility function proposed in Chapter 2. This in turn would mean that a user instead declaring her preferences over the QoS attribute will simply associate its type with the request. As we know that the user type is represented by $k \in \theta, \forall\{\theta_k|k \in \{\text{excellent, good, fair}\}\}$. For each user type there exist a user satisfaction range say $[u_{k,min}(\underline{MOS}), u_{k,max}(\overline{MOS})]$. Such information is the consequence of experimentation measurement values and utility function values mapping (as detailed in Chapter 2). We assume that MOS value ranges describing different user types is common knowledge i.e., all the stake-holders have such knowledge as priori. At this stage, one can think of two possible market behaviors; i) Users and operators come to an agreement over the service quality and price for the life time of the request (call), therefore the user needs not to collect (periodic / in event based fashion) any further information for alternate network selection for the life time of the call. ii) The network selection decision is triggered during the life time of a call owing to the degraded service, better alternate service price offers, etc. In this case the auction is carried out each time the call request arrives. This dictates that in the later case, the proposed model should also capture the operator handover costs in the network selection decision making. Such signaling cost function should be associated with the signalling overhead and processing load incurred when the handoff execution is performed.

Remark 4. *The handover or switchover costs are also the important part of the operator offers in the earlier case e.g., operators' offers include the estimated handovers and codec switchover costs for the lifetime of the call. User satisfaction behavior for such costs is modeled in Chapter 2.*

We assume that $C_{s,h}$ represent the aggregated estimated handover and switchover cost that operators expect would result during the life time of the call. Such cost is the function of user mobility, operators' deployed infrastructure in the geographical area, where the user is present. The value for such cost function may be found from the experimentation and generalized over the telecommunication footprint of the operator, (90) discusses the signalling costs and its computation. The computation of concrete signalling costs is out of the scope of this work. As mentioned earlier that user requests contain the expected range of MOS values for the service, which is the consequence of the mapping of technical indices over the MOS values for different types of users (Chapter 2). Upon receiving the user requests, the available operators within the area present their offers. These offers are evaluated if they fall within the user type specific MOS value range or rephrasing the sentence, we can say that only the potential operators (those who can offer the required service quality) can participate in the auction. The auctioneer running on the 3^{rd} party (architectural details realizing the auctions is detailed later in this chapter) selects the network operator that can best match the user expectations.

Remark 5. *Handover decision mechanism is triggered when i) users move out of the coverage area of current point of attachment. ii) Layer-2 measurements are degraded under some threshold. iii) User preferences profile is changed iv) Service associated attributes are degraded. v) Better alternate network / operator is available in terms of cost and other application associated attributes.*

3.6.1 Assumptions

We assume that the position of the UE in geographical area is periodically updated to the auctioneer. This dictates that the *auctioneer* knows the position of the mobile terminal, and in turn knows the telecommunication coverage footprint and where the a user is? However, the user may forward the velocity information with its request to the auctioneer. Since auctioneer knows the communication footprint in the whole geographical area, it means that network identifiers of different operator network technologies are also known to the *auctioneer*. The service charges is operator specific e.g., billing based on duration for voice calls and billing based on the volume of downloaded data for data services, etc. However in our approach, we assume that service charges are decided in each auction (per unit resource or per call basis). The *auctioneer* may reside at the mobile terminal or at the trusted 3^{rd} party. In case, it resides at the mobile terminal, then the auctioning format would be reverse auction (88). We also assume that user satisfaction function is a public knowledge and is available with auctioneer for different applications and user type. On the similar lines as explained in Chapter 2, we assume that users are categorized into three main categories based on their preferences namely; i) excellent, ii) good, and iii) fair users. We also know from the Chapter 2 that based on their preferences the users are characterized by their satisfaction functions which is scaled between [0-5] and is the consequence of user utility function transformation from QoS parameters. Operators incur different costs over extending different services over networks with different MOS values, this variation in the cost is influenced by the load over operator, operation and maintenance cost, and over provisioning of resources to the requests, etc. We assume that the operators declare their true cost function (true request valuation value) to the mediator. We also assume that each user is associated to a default operator network. This follows from a realistic assumption that all the involved entities have already agreed to the common protocol and are bound in SLAs based on different criteria.

Remark 6. *Network selection decision, when based on higher level i.e., MOS value level rather than more dynamic low level information (such as delay, packet loss, etc.) reduce the frequency of handovers to a greater extent. However, in such scenarios, user perceived QoS needs to be investigated and compared. It should also be noted that operator, if intend to implement simultaneous interface communication, such information may be forwarded through auctioneer.*

3.6.2 Settings

We examine a system with a finite number of users and operators. The set of user is denoted by $\mathcal{N} = \{1, 2, \ldots, n\}$ and finite number of operators $\mathcal{O} := \{1, 2, \ldots, m\}$. Each user has finite number of actions denoted by $\mathcal{A}_o \forall o \in \mathcal{O}$ (which may not be arbitrary large). Users generate the requests of different service classes, where requests are the elements of the application set $\mathcal{C} = \{$ video, audio, data (FTP)$\}$. Each service class element can further be sub-divided into quality classes with respect to user types i.e., excellent, good, and fair user types. These subdivisions are justified by our proposed user types i.e., user type is directly mapped over the service classes e.g., a user requesting excellent service is termed as excellent user type. Let the user request for the service be represented by $r_{k,c}$ and $a_{j,k,c}$ represents the allocation of operator resources to the user for type k and quality class c. Let $\pi_{j,k,c}(r_{j,k,c})$ represents the resource price that user pays against the services. Let $ci_{o,k,c}(a_{j,k,c})$ is the incurring costs of operators on the allocated resources to the user j. The environment settings dictate that users requests are auctioned via trusted 3^{rd} party amongst the available operators. We use the Vickery Clark and Groove (VCG) auctioning format to carry out the proposed user-centric network selection auction. The mentioned auction protocol is basically strategy proof i.e., declaring the true type is a dominant strategy for each bidder. Auction protocol is individual rational if no bidder suffers any loss in a dominant strategy equilibrium. We also know that the auction protocol is *pareto efficient* when the sum of all participants' utilities i.e., the social surplus, is maximized in a dominant strategy equilibrium. We now explicitly define the utility functions of users and operators.

3.6.3 User Utility Function

In this chapter, we make use of the user utility function that we proposed and explained in Chapter 2 and a slightly modified version of this utility function. It should be noted that using the earlier, we analyze the QoS indices triggers based network selection. However, using the later (slightly modified version of utility function), we model the network selection based on higher level parameter(s) i.e., we tie the gain component of user satisfaction function to achievable bandwidth and assume that the bandwidth parameter implicitly captures the dynamics of QoS indices values. The motivation to use the two flavors of utility function is driven by goals of the chapter, where we focus on investigating the impact of satisfaction function (in terms of ping-pong handovers, user satisfaction, etc.) on users' behavior when the network selection decisions are made at different levels. it should also be noted that experiments for validating the modified version of utility function were made on the similar lines as objective and subjective measurements in Chapter 2. We implicitly capture the impact of technical indices on the achievable bandwidth in the *gain function* component of the modified utility function. The *gain function* is quantified in terms of user's QoE denoted by $\nu_{j,k,c}$ and the second component of the utility function (i.e., *cost function*) is denoted by $\Pi_{j,k,c}$. The cost function is aggregated sum of the price that user pays against the extended service $\pi_{j,k,c}$ and the handover and switchover costs i.e., $\Pi_{j,k,c} = \pi_{j,k,c} + C_{h,sw}$.

$$U_j(\nu_{j,k,c}, \pi_{j,k,c}) := \nu_{j,k,c} - \Pi_{j,k,c}, \tag{3.9}$$

as can be seen that user utility function is quasi linear. The gain component is given by (which is similar to the bandwidth dependent utility function component of the user satisfaction as detailed in Chapter 2.):

$$\nu_{j,k,c} := \begin{cases} 0 & \text{if} \quad b_{k,c} < \underline{b}_{k,c} \\ \mu_{k,c}\left(\overline{b}_{\tilde{k},c} + (\overline{b}_{k,c} - \underline{b}_{k,c})\frac{1-e^{-\beta(b_{k,c}-\underline{b}_{k,c})}}{1-e^{-\beta(\overline{b}_{k,c}-\underline{b}_{k,c})}}\right) & \text{if} \quad \underline{b}_{k,c} \leq b_{k,c} \leq \overline{b}_{k,c} \\ \mu_{k,c} & \text{if} \quad b_{k,c} > \overline{b}_{c,k} \end{cases}$$

where $\mu_{k,c}$ represents the maximum achievable utility for k type user and c type service. $\overline{b}_{k,c}$ represent the upper bandwidth bound for a user type k $\forall \tilde{k} \neq k$ (and $\tilde{k}$ represents the type which requires lesser values of QoS indices than that of k), which when provided to the users, consequences in a maximum achievable QoE for service c. For the definitions of the variables in the function, refer to Chapter 2. We also pictorially present the gain function curves for different types of users and NRT service in Fig 3.4. The second component of the user utility

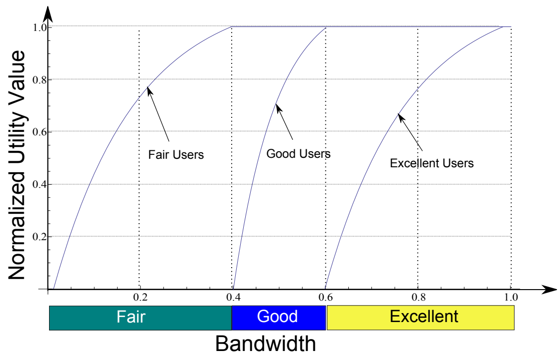


Figure 3.4: Different utility curves representing different user types - The figure plots the gain function for different k type users, the bandwidth bounds of each user type can be seen (e.g., for k = fair, $b_{fair,c}$ = [0.02, 0.4], $b_{good,c}$ =[0.4,0.6], etc.) It can also be noted that the maximum achievable utility value is scaled to 1. However, the maximum MOS value may be scaled to any desired value.

function is given by:

$$\pi(\delta_{k,c}) := \tilde{\lambda}\left(\overline{\pi}_{k,c} - \frac{\overline{\pi}_{k,c}}{\overline{\delta}_{k,c}}\delta_{k,c}\right), \tag{3.10}$$

where δ represents the users' gain for the offered service prices. $\tilde{\lambda}$ is the decision boolean, which takes the value of 1 if the operator offered bandwidth is at least equal to or greater than

minimum user required bandwidth and $zero$ otherwise. For the definitions of other involved variable refer to Chapter 2. The Equation 3.10 computes the price, which is equivalent to the price that user quotes and is willing to pay. A user will always quote his maximum willingness to pay, whereas the user pricing function is a common knowledge with the auctioneer.
We now pictorially describe the behavior of user for mentioned function (i.e., Equation 3.10) as shown in Fig 3.5.

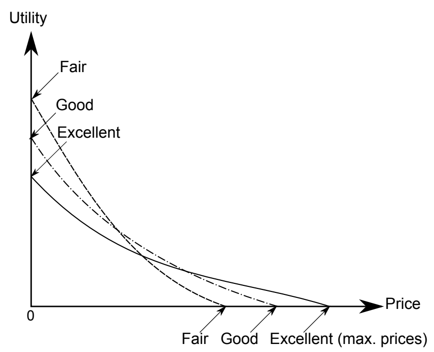


Figure 3.5: Price functions curves representing the behavior of different users - As evident that different users have different maximum price bounds for the service(s). The satisfaction of each user for different offered service price values result in utility values, which represent the sensitivity of users to the service prices.

3.6.4 Operator Utility Function

Each operator seeks to optimize the total revenue subject to user preferred QoS constraints. For each accepted user, the bandwidth allocation scheme(s) between the operator and users is established. This dictates that operator revenue is the function of resource utilization. Thus each operator designs the price function, we assume that operators sell out the resources on per unit basis. The proposed operator utility function also is quasi-linear and is given by:

$$U_o(\nu_{j,k,c}, ci_{k,c}) := \begin{cases} \sum\limits_{j\in\mathcal{N}} \pi_{j,c,k}(\nu_{k,c,j}) - \sum\limits_{j\in\mathcal{N}} ci(\nu_{k,c,j}) & \text{if} \quad \tilde{D} \leq b_{k,c,o}(\nu_{k,c,j}) \\ 0 & \text{if} \quad \tilde{D} \geq b_{k,c,o}(\nu_{k,c,j}) \\ \lambda \left(\sum\limits_{j\in\mathcal{N}} \pi_{j,c,k}(\nu_{k,c,j}) - \sum\limits_{i\in\mathcal{N}} ci(\nu_{k,c,j}) \right) & \text{if} \quad \tilde{D} = b_{k,c,o}(\nu_{k,c,j}) \end{cases} \tag{3.11}$$

where $\tilde{D} = max_{\tilde{o}\neq o} b_{k,c,\tilde{o}}$ is the maximum suitable bid if operator $o \in \mathcal{O}$ does not participate in the game. λ is tie breaking co-efficient that can take any value $\{0, 1\}$ randomly. The first component of the top expression in Equation 3.11 represents the aggregated revenue that operator earns from the amount of extended communication services to the user, whereas the second component within the same expression represent operator's incurring component within the same expression represent operator's incurring costs for the extended services. It should be noted that costs are computed on per unit resource basis. One could think of any suitable function to represent the cost. However, in this work, we assume that cost function is piecewise linear function, where the cost slope for each user type is denoted by $\alpha_{k,c,o}$.

$$ci_{k,c,o} = \begin{cases} \frac{b_{k,c}}{\alpha_{fair,o,c}} & \text{if} \quad k = \text{fair} \\ \frac{b_{fair,c}}{\alpha_{fair,o,c}} - \frac{5}{\alpha_{good,o,c}} + \frac{b_{k,c}}{\alpha_{good,o,c}} & \text{if} \quad k = \text{good} \\ \frac{b_{fair,c}}{\alpha_{fair,o,c}} - \frac{5}{\alpha_{good,o,c}} + \frac{b_{good,c}}{\alpha_{good,o,c}} - \frac{10}{\alpha_{excellent,o,c}} + \frac{b_{k,c}}{\alpha_{excellent,o,c}} & \text{if } k = \text{excellent} \end{cases}$$

The slope constants $\alpha_{fair,o,c}$, $\alpha_{good,o,c}$, and $\alpha_{excellent,o,c}$ are the slope constants that describe the operator cost offer slop for different user and service types. The values of the slope constants may be abstracted or approximated from the operators incurring cost models. We pictorially present the costs function of two different operators in Fig 3.6.

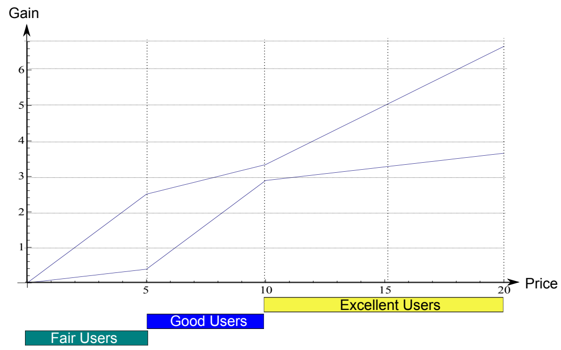


Figure 3.6: Price functions curves by different operators for different users - The two curves in the figure represent the operators' cost function behavior for different user types. The slopes of three different segments of each curve may be translated as the operators' target portion of the common user pool e.g., in the lower curve segment [0-5], the operator targets *fair* user more when compared with the upper curve, a similar pattern may be observed in segment [5-10] where the upper curve segment offers lower price offers and targets *good* users more as compared to the lower curve

It should be noted that cost component of the above function may be reduced to a generalized linear function whose slope and bounds are defined by user and service types. Fig 3.6 shows cost slope by two operators for different types of users. As can be seen that operators deployment strategies follow the operators' preference over the market share in terms of user types e.g., operator-1 (the upper curve) targets good users by offering lower service cost offers and operator 2 (the lower curve) is more interested in gaining fair and excellent users, this is also evident from the constant slope values. It can be observed that cost slope of operators can also be used to capture the operator's preference over target share of user pool i.e., an operator if not targeting the fair type users at some time of the day, simply offer true incurring cost plus the amount of cost that dictates the operator preference over the user type.

To show that auction protocol is *pareto efficient*, we define the *social surplus function* as the sum of all participants' utilities. Thus maximizing the *social surplus function* dictates the pareto efficiency. The social surplus function $F^{ss} = U_i(.) + U_j(.)$ is given by:

$$F^{ss} = \begin{cases} 0 & \text{if} \quad b_{k,c} < \underline{b}_{k,c} \\ \mu_{k,c}\left(\bar{b}_{\tilde{k},c} + (\bar{b}_{k,c} - \underline{b}_{k,c})\frac{1-e^{-\beta(b_{k,c}-\underline{b}_{k,c})}}{1-e^{-\beta(\bar{b}_{k,c}-\underline{b}_{k,c})}}\right) & \text{if} \quad \underline{b}_{k,c} \leq b_{k,c} \leq \bar{b}_{k,c} \\ \mu_{k,c} & \text{if} \quad b_{k,c} > \bar{b}_{k,c} \end{cases} - \begin{cases} \frac{b_{k,c}}{\alpha_{fair,o,c}} & \text{if} \quad k = \text{fair} \\ \frac{b_{k,c}}{\alpha_{fair,o,c}} - \frac{5}{\alpha_{good,o,c}} + \frac{b_{k,c}}{\alpha_{good,o,c}} & \text{if} \quad k = \text{good} \\ \frac{b_{fair,c}}{\alpha_{fair,o,c}} - \frac{5}{\alpha_{good,o,c}} + \frac{b_{good,c}}{\alpha_{good,o,c}} - \frac{10}{\alpha_{excellent,o,c}} + \frac{b_{k,c}}{\alpha_{excellent,o,c}} & \text{if } k = \text{excellent} \end{cases}$$

Now that we have defined the utility functions of all the involved stake-holders in network selection problem, we identify and model the decision problems and their location in the overall system. As evident from the formulation of the basic problem, the decision making entity is the *auctioneer*.

3.6.5 Auctioneer Problem

The problem at the auctioneer end is decision over the amount of resource allocation and price that user pays for the service. The auctioneer decisions are derived by the objective of maximizing the social surplus function. Let $a^*_{k,c}$ represent the optimal resource allocation and $\pi^*_{k,c}$ represent the optimal resource price. The operator gets per unit price $\pi^*(b_{k,c})$ equivalant to the second higher cost. The allocation $a^*_{k,c}$ is computed as:

$$a^*_{k,c} := argmax_{b_{k,c}} F^{ss} \tag{3.12}$$

Solving Equation 3.12 (by differentiating it w.r.t. offered bandwidth) one gets the value of $a^*_{k,c}$. The optimal price $\pi^*(b_{k,c})$ using the VCG auctioning mechanism is given by $\pi^*(b_{k,c}) = \hat{c}_{o,k,c}$, where the index o represents the operator (bidder) and $\hat{c}$ is given by:

$$\hat{c}_{i,k,c} := \{\pi | \pi = min(C_{-o\setminus\{\hat{o}\}})\} \tag{3.13}$$

where $C_{-o\backslash\{\hat{o}\}}$ represents the list of all the per unit costs quoted by operators except the winner operator indexed by $\hat{o}$. This dictates that the winner operator $\hat{o}$ will always have positive utility. This also guarantees the strategy proofness of the auctioning protocol.

3.6.6 User-Centric Network Selection Algorithm

We now implement the proposed user-centric network selection algorithm. The algorithm presented below is self explanatory. The algorithm resides at the *auctioneer* entity. The sequence of actions in the decision making is as:

1. The mobile terminal sends the request to the trusted 3^{rd} party, this in turn means that user has defined its preferences over the requested service. Such preference definition is very dynamic and may be associated with the user context i.e., a user may be excellent at one time instance and good at another. Similarly, a user at one time instance may set the preference of good user for FTP download, and of excellent user for VoIP service. This dictates that user request contains the service and user type.

   Note: As defined earlier that user types can be translated into different user profiles, which further is the function of various dependent and independent associated attributes (refer to Chapter 2).

2. Upon receiving the user requests (characterized by the user types), the auctioneer broadcasts the requests amongst the available network operators who own network technology(ies) in that coverage area.

3. The potential operators then make offers for the requested service.

4. Auctioneer computes the resource allocation a^* and π^* and inform both the winner operator and the user.

5. Repeat step $1 - 4$ for every auctioning instances.

3.7 Possible Realization Issues

Given the user-centric paradigm, where the users are independent of the network operators and have no long-term or default connection contract with any available operators, one can think of various technical issues. To highlight few of such issues, we formulate a few questions;

Algorithm 1: Calculate $a^*_{k,c}$ and $\pi^*_{k,c}$

Require: $a^*_{k,c} \geq \underline{b}_{k,c} \forall k \in \theta \wedge c \in \mathcal{C}$, t = 0
Ensure: $\underline{b}_{k,c} > 0$
$b_{req} \Leftarrow 1$, $\pi_{dec} = 0$ // Initialize the variables of request and price
$\pi_{dec} \Leftarrow 0$
if $(k \in \theta)$ **then**
  $b_{req} \Leftarrow \overline{b}_{k,c}$
  $\underline{b} \Leftarrow \underline{b}_{k,c}$
end if
$R \leftarrow r_{j,k,c}$ // Update the auctioneer request vector
LIST$\hat{C} \leftarrow c_{o,k,c}$ // Update the auctioneer bids vector
while $\hat{C} \neq 0$ **do**
  $cost_o \leftarrow \hat{C}.c_o$
  $a^*_{k,c} \leftarrow F^{ss}(cost_o \wedge r_{j,k,c})$
  SORT $LIST\hat{C}$
  $\pi^*_{j,k,c} \leftarrow LIST\hat{C}.\underline{c} + 1$ //select the second highest cost
end while

- **Q-1:** When the user turns the mobile ON, what will be his default connection operator?
- **Q-2:** Provided one assumes that there exists a default connection provider, how does the network selection decision making execute on technical grounds?
- **Q-3:** How is the user authentication carried out?
- **Q-4:** How is the user context information transferred?
- **Q-5:** How are the technologies or different operators integrated?

In this chapter, we make an attempt to answer these questions and present the architectural solution that realizes the user-centric approach for the proposed solution. We address these issues on granule level.

3.8 The Architectural Realization Solution

We now present the architectural solution that realizes the proposed user-centric network selection approach. We select LTE and WLAN network access technologies owing to their envisioned widely use in the future wireless communication. These RANs are connected to the core network of the operator. Here we focus on two main aspects; i) intra-operator network technologies integration architectural solution and ii) user-centric inter-operator network selection architectural solution.

3.8.1 Intra-Operator Architectural Solution

As widely accepted that the 4G networks will purely be IP based, and will be characterized by the independent drivers, such as *users*, *network operators*, and *service providers*, etc. Given the requirements of adopting the system to the user-centric vision, for an operator mobility management turns out to be a crucial issue for the operators. Owing to the maturity of current communication paradigm, it is needless to highlight the importance heterogeneous wireless technologies and their co-existence to extend services to the users. When it comes to heterogeneous wireless technologies, one can discern various prevailing standards in the current communication market, such as 3GPP, non-3GPP, 3GPP2, etc. Both 3GPP and non-3GPP are of core importance, however the difference is dictated by the preference of incumbent and the new entrants, for example an incumbent operator with its infrastructure in place is comfortable with 3GPP technologies, whereas the non-3GPP technologies are the technologies of choice for new entrants. Now that the market is framed to accept both the 3GPP and non-3GPP technologies, this provisions that end-consumers should be enabled to make efficient use of the services extended through both the technologies. Intuitively the objective function of operators will include the profit maximization through integration of 3GPP and non-3GPP technologies. A good news is that 3GPP has come up with standards for such integration, Fig 3.7 represents such an integration architecture.

Given the integration solution, incumbent operators might prefer to hold the market by deploying the non-3GPP technologies. In this case although the operators are better off by providing diversified interfaces to the end-consumers, they are faced with crucial mobility management issues. Thanks to 3GPP that addresses these issues and provide mobility management solutions for different use cases. Let us now have a birds eye view over the solutions; basically non-3GPP technologies can be integrated with 3GPP technologies through one of the three interfaces (S2a, S2b, S2c) provided by Evolved Packet Core (EPC) / System Architecture Evolution (SAE). The description of the each interface is as follows:

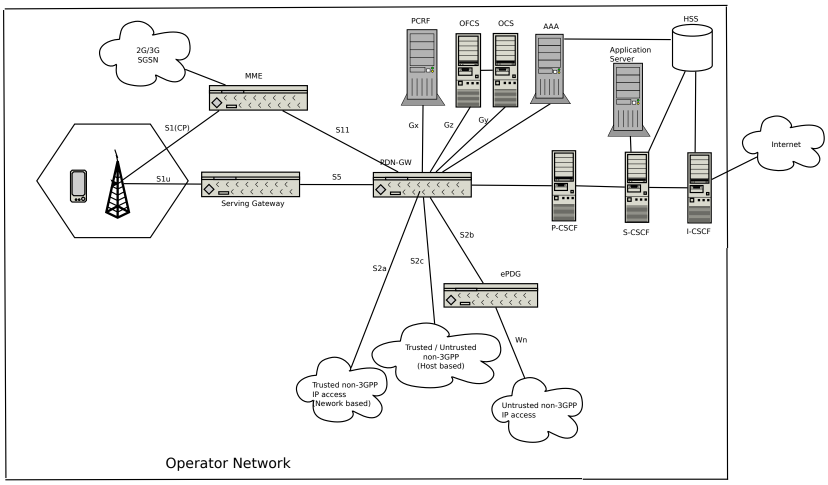


Figure 3.7: Intra-operator heterogeneous technologies integration architectural solution - The figure details the proposed heterogeneous architecture based on 3GPP standards. We term this as the intra-operator architectural solution owing to the fact that the core network is owned by a single operator to which all the heterogeneous wireless access network are associated (in this case LTE and WLAN integration can be seen).

- S2a: It provides the integration path between the trusted non-3GPP IP networks and 3GPP networks. In this case the mobility is handled by the network based mobility solution, e.g. Proxy MIPv6.

- S2b: It provides the integration path between the un-trusted non-3GPP IP networks and 3GPP networks. In this case the mobility is handled by the network based mobility solution.

- S2c: It provides the integration path between both trusted and un-trusted non-3GPP IP networks and 3GPP networks. In this case the mobility is handled by the host based mobility solution, e.g. Dual Stack MIPv6.

The details of procedures for each interface solution is as follows:
In case of S2a solution, after L2 attachment with non-3GPP access point, the AAA authentication procedure is performed. Upon the successful authorization and authentication, L3 /IP attachment procedures are triggered. In this case the non-3GPP access point takes the role of Medium Access Gateway (MAG) and sends proxy binding update message to Packet Data Network - Gateway (PDN-GW). PDN-GW updates its address to 3GPP AAA server followed by proxy binding update procedures, which results in IP address allocation for UE. The UE

IP address is then sent within proxy binding update acknowledgement message to non-3GPP access point. This creates proxy MIPv6 tunnel between non-3GPP access point and PDN-GW and this completes the L3 attachment procedure and results in IP connectivity establishment between UE and PDN-GW.

In case of S2b solution, owing to involvement of untrusted non-3GPP access, a secure IP tunnel is required between ePDG and UE. In this connection MAG functionality is performed by the ePDG. The other procedures are carried out on the similar lines as explained for S2a.

In case of S2c solution, since we are faced with two different scenarios i.e., access through trusted non-3GPP and access through untrusted non-3GPP technologies. For the earlier case UE is assumed to be in its home network and therefore no tunneling is required. However in the later case an IPSec tunneling is required. The IPSec tunnel must be established between UE and evolved Packet Data Gateway (ePDG).

Note: More on the literature relevant to the proposed architecture can be found in (91, 92, 93). The readers are also encouraged to refer to (94) for background knowledge on MIPv6 and MCoA concepts.

Remark 7. *It should be noted that MIPv6 solves the problem of mobility when one interface at time is used, for the situations where simultaneous multiple interfaces are used the mentioned MIPv6 solution is insufficient. According to Mobile IPv6 RFC 3775 (95), a user is not allowed to use multiple active network connections simultaneously. However, there is an extension RFC 5648 (96) that deals how mobility protocols can be modified to allow mobile devices using multiple connections simultaneously. This task is referred as multiple care-of addresses (MCoA) registration in Mobile IPv6 terminology.*

3.8.1.1 MCoA Protocol Operation

All the nodes that implement this specification maintain an ordered list of CoA according to their BID-PRI. The CoA with the highest priority is considered as default CoA for all packets which cannot be handled using registered flow management policies. MN can add, modify, refresh, or delete flow bindings by including Flow Identification or Flow Summary mobility options in binding update message. For example; i) New flow binding - MN sends Flow Identification mobility option in BU message with a unique FID which is associated with one of already registered CoA of MN. A Flow Binding must have exactly one Traffic Selector. ii) Updating flow binding - With flow binding update procedure the MN can change the priority, the BID(s), and/or the traffic selector associated with a flow binding. However, if no modification is required traffic selector and binding reference sub option may be omitted. iii) Refreshing flow binding - MN must refresh all of its flow bindings in every binding update message even if it does not want to change any of their parameters. Flow bindings can be refreshed by sending flow summary option. iv) Removing flow binding - Removal of flow binding entries is performed implicitly by omission of a given FID from a binding update. v) Returning home - If the MN performs an RFC3775 (95) style deregistration, all of its bindings, including flow bindings are deleted. If the MN, however, performs an RFC5648 (96) style home registration, then the home link is associated with a specific BID and so it is treated as any other link associated with a given BID. vi) Binding acknowledgement - A binding acknowledgement message in response to in response to a Binding Update with flow identification mobility option must include flow identification option otherwise it would be an indication of inability (or unwillingness) on behalf of the source node to support the extensions presented in this specification. vi) Route optimization - Before sending a Binding Update to correspondent node, the Return Routability Procedure needs to be performed between the mobile node and the correspondent node. This procedure is not affected by the extensions defined in this specification.

3.8.2 User-Centric Inter-Operator Network Selection Architectural Solution

This section focuses on the practical implementation of the proposed approach in inter-operator network selection scenarios, the architecture is IMS based [3GPP TS 22.228 release 5]. It should be noted that general assumption discussed in sub-section 3.6.1 remain valid within this architecture. The motivation to base our proposed architectural solution comes from the following attractive characteristics of IMS:

- IMS supports the establishment of IP multi-media sessions, suggests the mechanism to negotiate QoS, provides solutions to interworking with the internet and circuit switched networks and roaming, provides strong control imposed by the operator with respect to the service delivered to the end-user, and supports rapid service creation without requiring standardization.

- IMS also provides the controlling gear to the operators for differentiating different user groups and accordingly controlling the QoS a user gets based on the users' subscription or the network state. IMS is just an IP network, which is access layer independent, thus any access network can in principle provide access to the IMS.

3.8.2.1 Functional Components of the Architecture

In Fig 3.8, we present the proposed inter-operator network selection architectural solution. As can be viewed that the operator networks communicate through trusted 3^{rd} party. We categorize the architecture in three major functional entities. Such decomposition of the architecture is driven by the fact that mainly interaction takes place among these entities. In the following, we elaborate on these entities.

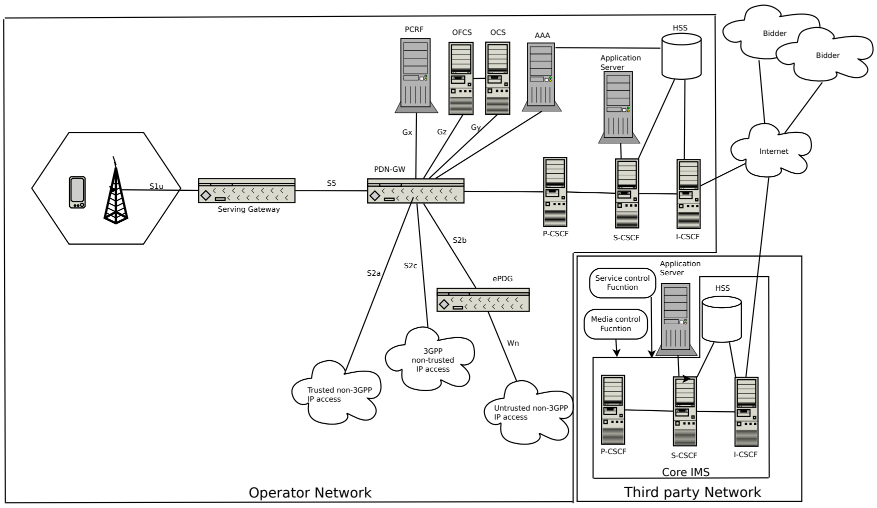


Figure 3.8: The Proposed IMS based inter-operator architectural solution for user-centric network selection - The bigger block represents the architectural entities and their integration at operator-end, whereas the smaller block shows the integration of entities at the 3^{rd} party

Auctioneer functional entity ($3^{rd}party$) **:** It is a SIP application server, which processes SIP messages formulated using the SIP MESSAGE method from UE and operators. We use MESSAGE methods commonly used for Instant Messaging and application control messages. It is assumed that SIP application running on the *Auctioneer* understands XML messages, which are enclosed in the message body of proposed SIP message method (i.e., MESSAGE). Examples of such MESSAGE methods can be seen in Fig 3.9. The figure represents the user generated MESSAGE method. The MESSAGE method body contains; i) request of service type, ii) user preference over the service quality, which is captured by the user type, and iii) user identity information such as ISIM number, etc. Similarly, the SIP MESSAGE method body from the operators (bidders) to the auctioneer is shown in Fig 3.10. As can be seen that the message body contains; i) offers containing the estimated incuring cost functions of all the service types and cost functions for different supported service quality levels (which is translated into user types) of all service types.

UE functional entity: As assumed that UE gets associated with the 3^{rd} party , thus upon initiating the call, UE selects the service type and define her preferences over the service quality level by indicating the *user-type*. For the proposed approach, this information is adequate to be sent to the *auctioneer*. UE puts this information into the body of SIP MESSAGE (as shown in Fig 3.9) and sends the SIP MESSAGE to the auctioneer.

```
MESSAGE sip:auctioneer1@3rdparty.com SIP/2.0
Max-Forwards: 70
From: Alice <sip:alice@defaultNetwork.com>; tag=1928301774
To:  3rd Party auctioneer <sip:auctioneer1@3rdparty.com>
Call-ID: 1928301774@defaultNetwork.com
CSeq: 1123122 MESSAGE
Auction-Information: Session bidding request
Content-Type: text/plain
Content-Length: xxx

<?xml version="1.0" encoding="UTF-8" ?>
<TypeOfService>VoIP Call</TypeOfService>
<ServiceQualityPreference>Fair</ServiceQualityPreference>
<UserIdentity type="ISIM">909009900909</UserIdentity>
```

Figure 3.9: User generated SIP message method - The message is addressed to the 3^{rd} party. As can be seen that the MESSAGE body contains user requested service type. User preferred service quality is captured by declaring user type (in this example, the user type is *fair*. In addition to the mentioned information, user request defines the call ID, encoding type, etc. which are self explanatory.)

Bidder functional entity: Bidders in the proposed approach are analogous to the operators. They are indirectly associated with service consumers through the trusted 3^{rd} party. This dictates that they need to update their potential or status to the *auctioneer* i.e., their estimated cost component of the utility function for different quality levels and for different services. By the potential operator here, we mean the operator strength / capability to support the user requested service ensuring some level of quality. The operator's strength can be translated as operator infrastructure deployment or other quality enhancement measures implemented by the operators. The bidder communicate with UE entity through Auctioneer entity by sending SIP based MESSAGEs containing the service offers against user requests. An example of such bidders' MESSAGE is shown in Fig 3.10, which is sent by the bidder functional entity to the auctioneer. As can be seen in the MESSAGE body that operator quotes the offers for the user generated request with associated user preferred QoS class (in this example, operator extends the offer for VoIP call request of *fair* type users and for FTP service request of *excellent* type users). It can also be noted that expiry time of the offer is also identified by the operator, which means the offer is not valid after the laps of defined life time of offer. One can also notice that offer varies in the cost field (explained in section 3.6.4).

```
MESSAGE sip:auctioneer1@3rdparty.com SIP/2.0
Max-Forwards: 70
To:  3rd Party auctioneer <sip:auctioneer1@3rdparty.com>
From: Bidder1 <sip:bidder@operator1.net >; tag=1928301774
Call-ID: 3s09cs03
CSeq: 1343322 MESSAGE
Auction-Information: Cost information registration
Content-Type: text/plain
Content-Length: xxx

<?xml version="1.0" encoding="UTF-8" ?>
<CostInformation>
<TypeOfService>VoIP Call</TypeOfService>
<ServiceQualityPreference>Fair</ServiceQualityPreference>
<CostFunctionParameter>12</CostFunctionParameter>
<LifeTime unit="seconds">3600</LifeTime>
</CostInformation>
<CostInformation>
<TypeOfService>FTP Download</TypeOfService>
<ServiceQualityPreference>Excellent</ServiceQualityPreference>
<CostFunctionParameter>12</CostFunctionParameter>
<LifeTime unit="minutes">30</LifeTime>
</CostInformation>
```

Figure 3.10: Operator generated SIP MESSAGE indicating the cost update for the requested user request - The SIP MESSAGE method showing the cost updates sent by the operator to the third party. The MESSAGE body include type of service and quality class for which the cost is updated.

Remark 8. *Although we follow the protocol, where against every broadcasted user requested services, the operator submit offers, the proposed approach is generic enough to implement the protocol in which bidders periodically submit for all the services and defined quality types. Auctioneer broadcasts these offers to the user pool. We also implement this approach in the configuration where the handover can be triggered during the lifetime of the call.*

3.9 Sequence of Operation - A detailed view

We now illustrate the operational details within the proposed architecture. In this connection, we decompose the interaction into; i) Auctioneer - operator and ii) UE and auctioneer interaction. The sequence and details of both the interaction environments are in the following subsections.

3.9.1 Auctioneer - Operators environment

All the operators in the coverage area have contractual agreements with the auctioneer (e.g., Service Level Agreements (SLA)), and have agreed to periodically update their potential information to the auctioneer for different services and user types. On more granule level it can be thought of as giving in the cost functions of operators, which are operator specific. However, the controlling parameters of the cost function, $\alpha_{fair,o,c}$, $\alpha_{good,o,c}$, and $\alpha_{excellent,o,c}$ $\forall o \in \mathcal{O}$ which are dynamic and influenced by the operator load, congestion level and different other aspects are sent in to auctioneer periodically. After the request association decision by the auctioneer, the operator(s) is informed about the decided quality level and agreed service price.

Remark 9. *It should be noted that the quoted value of α is also driven by the operator policy to target some specific user type(s) from the common user pool. Putting it the other way, operator cost offers may also be translated as operators' private valuation of the users' requests, which may or may not be the true incurring costs of operators.*

3.9.2 UE - Auctioneer environment

As illustrated in the assumption section that users are free to be associated to any available operator via auctioneer. This environment is more an event-based environment, driven by the user request generation. Users interaction with auctioneer is limited to declaring the type of service request, preferred quality level, the price that user is willing to pay for the service. Now that environments are defined, we are in position to detail the sequence of operation.

1. User when switches the UE ON, she gets associated to IMS plateform of the default network operator.

2. After successfully completing the registration process, UE can now proceed towards the establishment of intended or requested session. These session may use either IMS or non-IMS plateforms.

3. Now if the user wants to initiate a call, she constructs the SIP MESSAGE by specifying the service type, preferred quality level of the requested service, and her identity. This is illustrated in Fig 3.9, where the used case is that *fair type* user declares her preferences for the VoIP service, service cost preferences, the service cost validation period, and the user identity is represented by the IMS identifier

4. The MESSAGE forwarding takes the following route; UE $\rightarrow$ Proxy Call Session Control Function (P-CSCF) $\rightarrow$ Serving CSCF (S-CSCF) $\rightarrow$ Application Server (AS). It should be noted that P-CSCF and S-CSCF functional components belong to the default operator and AS belongs to the trusted third party (Auctioneer).

5. Upon reception of the MESSAGE the 3^{rd} party (Auctioneer) application server extracts the service request parameters from the message body and generates one of the two possible MESSAGEs i.e., i) the bidding mechanism has successfully resulted in resource allocation and service price decisions. These decisions are executed by generating the two simultaneous responses; of which one goes to UE indicating the successful operation and the other is sent to the winner operator. ii) the bidding mechanism resulted in blocked call owing to the fact that with reported potential of operators the requested service can not be entertained.

6. One of the MESSAGEs generated in step-5 serves as a notification of winning to the winner bidder. This MESSAGE further contains the user identification, details about the session that is to be conducted by the winner bidder, and the price that user pays for its service.

7. Upon receiving the MESSAGE, the winner bidder stores all the related information as a short term policy in the SPR (Subscription Profile Repository), which enables the user to get associated with the network and conduct his intended session using the access network of the winner bidder. It is assumed that there exists an interface between SPR and bidder functional entity for updating such short term policies.

8. The second MESSAGE generated in step-5 is received by UE, which contains the information of winner bidder and the price that user has to pay for the service. UE now has to get associated with the winner network operator which is a visited network for the UE. As assumed earlier that contracts exist between network operators and auctioneer over different lines, we also assume that such contracts encamps the inter-operator visitor entertaining contracts and billing procedures.

9. After performing AAA and L3 procedures, the UE gets an IP address and SIP identity. Now the user is enabled to register its current location with the home IMS network (for details refer to section 3.10).

3.10 Protocol Operation Considerations

In this sub-section, we elaborate on the protocol operation considerations of all the involved entities in the proposed user-centric network selection.

3.10.1 Bidder Function Entity

The functions carried out by this functional entity are listed below:

- In case network operator wants to participate in the auction, it must configure this SIP application server to register its parameters for the indicated time length. This entity can formulate one SIP MESSAGE for one service or multiple cost functions information for multiple services using one SIP MESSAGE. However, in multiple cost functions case care should be taken that SIP message size does not exceed the upper bound defined by IETF standards for SIP messages (the standard says that SIP message should at least 200 bytes less than the lowest MTU value found en-route to the 3^{rd} party).

- The registration of cost information for any particular type of service will automatically expire and will be deleted from the third party auctioneer AS after the indicated life time (which is mentioned as a part of the registration).

- The registration offer can dynamically be modified any time by sending another SIP message with new operator information that overwrites the previous registration information. This process can also be used to delete the registration information by sending an update information in SIP message with $zero$ life time.

- This entity should maintain the record of all its sent information because such information can not be retrieved from the auctioneer application server.

- In order to ensure the error free delivery of the SIP MESSAGE containing the registration cost function information to auctioneer should be delivered over the TCP. Moreover it is assumed that there exists a secure link between bidder functional entity and auctioneer AS, which can be achieved using IPsec tunnel.

- This entity should be always prepared to receive a notification from the auctioneer indicating the allocation resource decision, which auctioneer only generates if the operator turns out to be the winner bidder. This notification is sent as a SIP MESSAGE containing information about the service type, user preference, user identity, and the service price.

- This entity should be able to formulate a compatible policy that enable users to get authenticated and conduct the entitled session. The interface between Subscriber Profile Repository (SPR) and this entity is operator specific.

- It should be noted that in response to SIP MESSAGE from this entity, a SIP specified acknowledgement response must be sent by the auctioneer that indicates the status of registration process. Basically the acknowledgement methods in this case may be an "OK" or any other error message, however handling the error messages is out of the scope of this work.

- This entity keeps track of the registration and their acknowledgements using Command Sequence (CSeq) header field.

3.10.2 UE Entity

- It is assumed that user is already in his default network and has successfully performed the SIP registration with IMS plateform of the default network. Now if the user wants to conduct a session as per proposed mechanism then he must include the type of service, its preferences and its identity in regulation of allowed xml syntax and send this information in the body SIP MESSAGE to the auctioneer. Here we assume that SIP URI (Uniform Resource Identifier) of the auctioneer is known to the users as part of the contract. A user must send only one session request in one SIP message.

- UE should be able to parse the information received as the part of response that is sent by the 3^{rd} party against its request. The response can basically consequence in to user request accepted or blocked. Let us now deal with these response types discretely.

  In case of call block: This case is indicated by the SIP MESSAGE. UE has the option to compromise over the declared preferences and repeat the process of acquiring network resources. Other alternatives include; UE attempts to get associated with other third party auctioneer in the market, sends a SIP MESSAGE to the current auctioneer requiring that UE should be informed about the availability of required resources with the current preferences with the help of SIP MESSAGE, or UE follows the auctioneer suggested preference setting pattern and set the new service preferences, however the details of these alternative solutions are out of the scope.

  In case of call acceptance: This case is indicated by SIP MESSAGE. Furthermore the message response body contains the information about the target point of attachment (the winner bidder) as well as the price that user has to pay and the time validity of this offer. User parses this information and connects to the indicated network.

In case of request rejection: This case is indicated by the error status code, which could be SIP specified standard or any other extensions for handling rejections.

After the successful association of user with the winner bidder, he has the option to register himself with his default IMS plateform through the visited network. After session termination, the user disconnects from the visited network (and connects to its default network and perform the optional IMS registration).

3.10.3 Auctioneer Functional Entity

This is implemented as two logical functions; one is the bidding engine and the other is SIP server. As a SIP server, it receives standard SIP MESSAGEs with the body part containing information which is required to run the proposed mechanism. It interacts with two types of entities, on upstream it interacts with the bidders (operators), whereas on the downstream it interacts with the users.

- Interaction with users: It receives user requests as SIP MESSAGEs, the body part of SIP MESSAGE contains the user requested service type, preferences as well as user ID. This entity should be able to parse that information and forward it to the bidding engine. The output of which is the call acceptance or call block. Any error that occurs within this process must be sent back to the user in response to the received SIP message. Further details of this interaction overlaps with the details provided in the subsection 3.10.2.

- Interaction with bidders: This entity receives cost information of supported services from the bidders which is included in the body part of SIP MESSAGE, which we term as registration for that particular supported service. This information includes the type of service quality preference, cost function parameters as well as life time of this registration. This entity should be able to parse this information and forward it to the database of bidding engine. This process consequences either in a success or an error, which is sent to the corresponding bidder in SIP MESSAGEs.

  In case a network operator wins the bid, then Auctioneer must inform the winner bidder through the SIP MESSAGE. The body of the SIP MESSAGE includes the user identity, type of service, preference over services, time validity.

3.10.4 Realization of Proposed Approach though MIPv6 based Flow Management

Since in the proposed solution mobile node is enabled to be associated with multiple networks for different services, therefore flow management is of prime importance. In MIPv6 the mobile node register its active interfaces with its home agent(HA), through Multiple Care of Addresses(MCoA) registration mechanism and also instructs its HA, by sending filter rules, how its traffic should be distributed over its registered CoAs. After successful registration of CoAs and filter rules, HA now starts intercepting MN destined traffic in its home network and sorts out, using filter rules sent by MN, which traffic flow should be tunneled to which CoA of MN. Hence MN this way, can use all of its network attachments for receiving traffic as well as manage bandwidth resources by specifying which type of traffic it wants to receive over a certain network interface. Flow identification option in MIPv6 header is used to establish flow bindings between MN and HA/CN. Just like a regular binding which is used to inform receiver about the current location of MN, flow binding is used to send filter rules to the other end. These flow bindings can be refreshed, removed and also get expired. A flow binding is identified by a unique integer number (Flow ID) and is always associated with a certain CoA. Therefore a flow binding message is usually piggybacked on its associated CoA's binding message. Details about all the protocols involved in realizing the flow management are provided earlier in this chapter.

3.11 Results and Analysis

To investigate the performance of the proposed user-centric network selection approach, we implement the resource allocation and price computation algorithm in a multi-operators multi-technologies scenario. The simulation is implemented using OPNET modeler 15.0. In order to realize the proposed flow management, we extensively implemented MIPv6 based flow management and flow label concept therein for managing different flows using OPNET. The reason for implementing the flow management is twofold; i) flow management enables us to realize the proposed user-centric network selection approach, establish multiple connections with different operators for different applications. ii) help us realize the concept of network centric resource allocation (refer to Chapter 5), where we suggest flow splitting solution to optimally utilize the operator resources. The simulation environment is shown in Fig 3.11, where two operators deploy their LTE and WLAN technologies (one each), those are coupled using

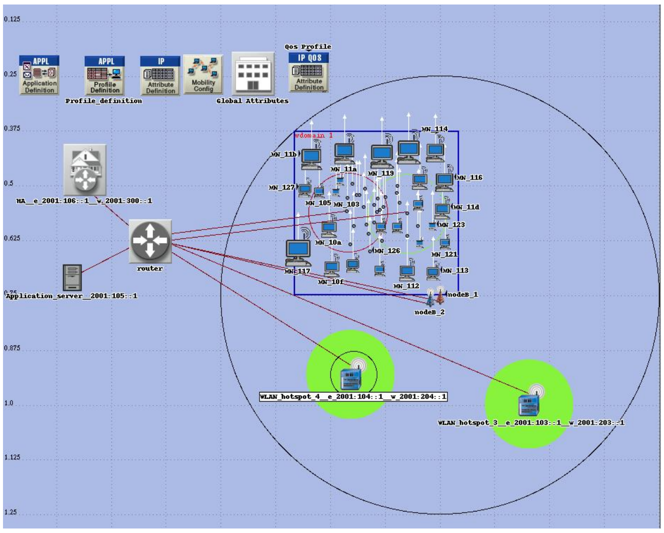


Figure 3.11: Simulation Environment - Figure depicts the OPNET simulation scenario. As can be viewed that implementation of heterogeneous wireless access network technologies (LTE and WLAN) and their integration consequence in various coverage areas. However, the focus of this work is the coverage area highlighted by a square area.

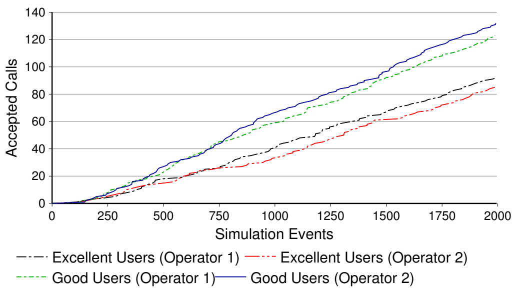
the intra-operator technology integration solution discussed in section-3.8.1. This defines the simulation coverage area, where LTE technology covers the whole area and WLANs cover it partially, this results in different overlapping coverage areas, for instance, the area covered by both the technologies of same operator and different technologies of same / different operators. We concentrate on one of such overlapping areas (as shown in the square in Fig 3.11) for our analysis, the choice of this area is influenced by the fact that the analysis within this area enables us to investigate the multi-operator scenario. We use OPNET standard WLAN IEEE 802.11b technologies with coverage radius of 90 meters and shaping rate 4Mbps. LTE used in this simulation is our contributed OPNET model with coverage radius set to 1000 meters and shaping rate to 2Mbps. There are in total 42 good type users and 8 excellent type users. These users are characterized by different DiffServ weights, in our case excellent type users and good type users are assigned weights of 10 and 1 respectively. Users generate FTP requests of 1MB file, the inter-request time is exponentially distributed with mean 260 seconds. The system load is calculated as; *Let operator's load is given by y times the number of associated users, where y =file-size / Inter arrival time. The total system load is the aggregated load of available operators.* We carry out simulations in the following simulation configurations: i) When both the operators have the similar potential. ii) When the available operators have different cost slopes for all the users and services.

3.11.1 When Both the Operators Have the Similar Potential

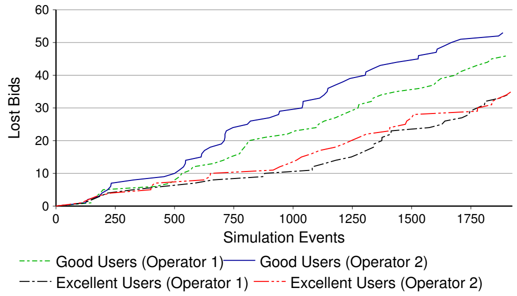
By the *operator potential*, we mean that operators incur similar costs on extending services. This can be thought of as the environment, where both the operators deploy similar infrastructure and incur somewhat similar operation and maintenance costs. It can also be taken as the operator private valuation for the extended services. However, it should be noted operators' incurred costs (private valuation) are different for different types of services. Intuitively, it is expected that both the operators compete neck to neck with each other for the user generated requests from the common user pool.

In this setting, we further assume that there are two types of users in the system namely *excellent* and *good* users, however the results may be generalized to all types of users. Since both the operators have equal potential in the current setting of telecom market, it is realistic to assume that both the operators set the market behavior and operators ensure the extension of nearly similar service quality and cost offers to the users. In this configuration, we set the cost slopes of both the operator as 1.2 and 1 for *good* and *excellent* type users respectively. Selecting the similar cost slope value (i.e., $\alpha_{good,op-1} = \alpha_{good,op-2} = 1.2$ & $\alpha_{excellent,op-1} = \alpha_{excellent,op-2} = 1$) is justified by the argument that both operators have the similar potential. We run the simulations for 2000-6000 runs, and analyze the following; i) admitted calls by both the operators, ii) incurring costs of operators, iii) users perceived QoS for the service, and iv) operators' revenue.

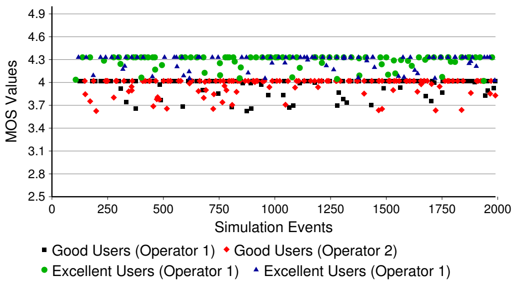
Fig 3.12(a) presents the results for accepted calls of *good* and *excellent* type users in the considered scenario. As evident from the curves in the figures that both the operators on average win the same proportion of the common user pool. Operator 2 accepts 57.64% more *excellent* type user requests than that of *good* type user requests. Similarly operator 1 accepts 32.6% more *good* type user requests. However, one can easily analyze that the call acceptance pattern of both the operators remain in close proximity i.e., on average the aggregated amount of call accepted by operator 2 is just 5.55% more than that of operator 1. To investigate the operator's incurring costs (incurring costs reflect the cost component of operator utility function), we run heavy rounds of simulations and observe that a there is a fractional change in the incurring cost of operator for different types of services. However, similar to the observation made in accepted calls analysis. The incurring costs of both the operators remain within the same range i.e., $0.6 - 1.3$. It should be noted that the aggregated cost component is normalized and scaled



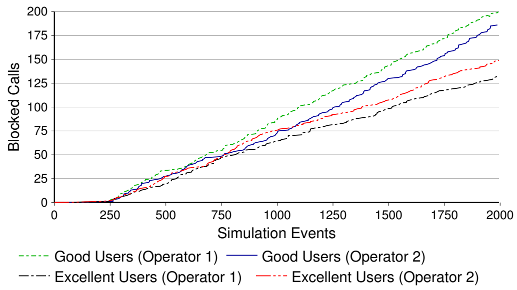
(a) Accepted calls by both the operators



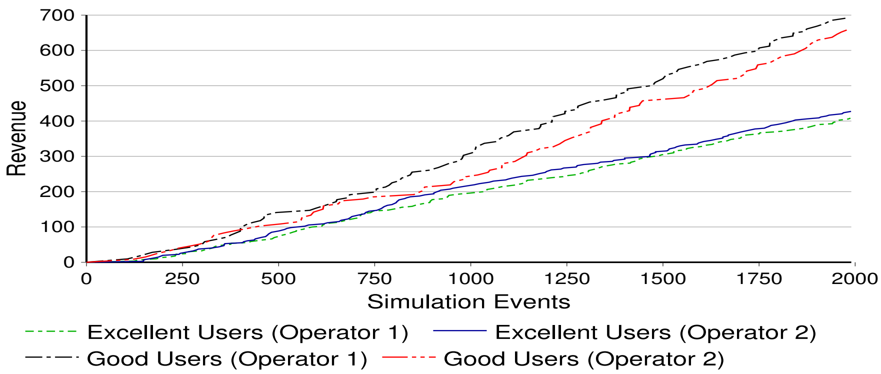
(b) Operators' Lost bids for service requests of different user type



(c) User perceived QoS for different extended services



(d) Blocked calls due to scarce resource radio resources



(e) Operators' revenues

Figure 3.12: Performance analysis of proposed approach in homogeneous settings for different performance evaluation parameters

between the range $0 - 1.5$. This is done for simplicity of the analysis. One can discretely study the monitory (service costs) and the signalling costs and then aggregate these costs following a weighted sum like approach. We also investigate the lost bids by operators in Fig 3.12(b). By the lost bid, we mean the user request that operator does not win due to its high price offers or lower QoS level offers. As evident from the figure that operator 2 drops 10.4% more *good* type user requests when compared with operator 1. However, when it comes to *excellent* type user requests, both the operators drop nearly the same amount of calls i.e., 36 calls. The motivating force to investigate the call drop patterns due to higher costs is to study the impact of higher costs or higher operator private valuation over the user behavior, which may consequence in under utilization of operator resources or increased churn out rate of the operators in long run. The results of user QoS perception are presented in Fig 3.12(c). It may be observed that user perceived QoS remains within the defined bounds for both the user types i.e., $3.6-4$ for good $\&$ $4-4.5$ for *excellent* users. This justifies that both the operators and users come to an agreement (at the time of call admission), then the operators guarantee the agreed service quality for the duration of the call. However, the event based or triggers based network selection mechanism is studied and presented in the section 3.12, where the network selection decision mechanism is triggered on the arrival of any trigger caused by service quality degradation or availability of better alternative during the lifetime of the call. The call blocking rate observed by the each operator is investigated in Fig 3.12(d). It should be noted that call block rate is translated as the number of those calls, which were blocked due to unavailability of resources. These do not involve the dropped calls due to high service prices (i.e., lost bids). As evident from the curves that on one hand operator 1 blocks 6.3% more calls from *good* type users, whereas on the other hand this operator performs better when it comes to *excellent* type users by blocking 18.11% lesser requests when compared with operator 2.

We conclude our investigation within this configuration by analyzing the revenue of both the operators where revenue curves are the consequence of operators' utility function. Fig 3.12(e) represent the profit of both the operators. Operator 1 performs partially better when it comes to revenue earned from entertaining *good* type users, this behavior is also reflected in Fig 3.12(a), where operator 2 accepts more calls. A somewhat similar behavior can be observed when analyzing the profit earned by extending services to excellent type users.

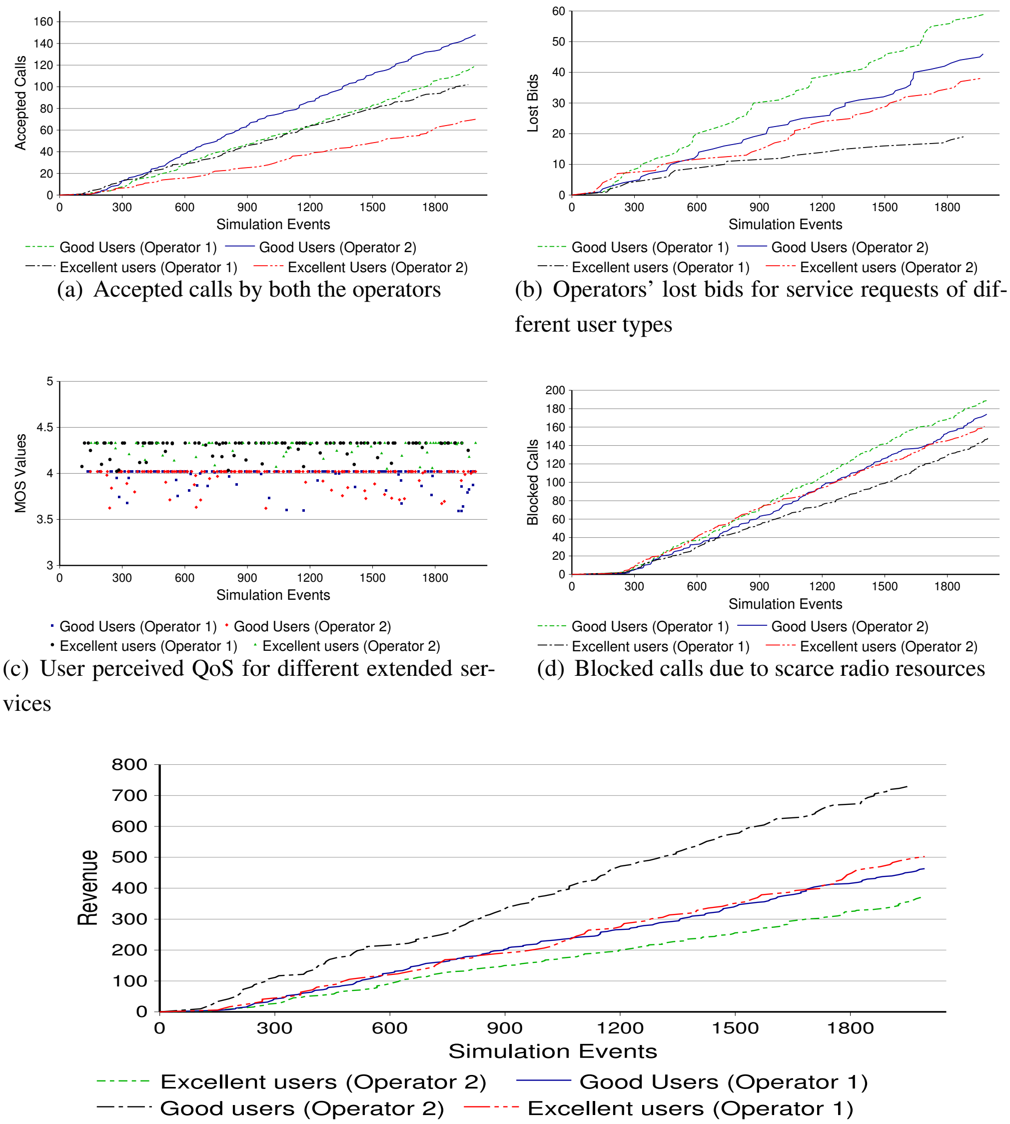
Thus from the analysis, we conclude that operators with the similar potential when follow the market dynamics (i.e., adapt service pricing and technology update as per user and service demands) behave in somewhat similar fashion. This further motivates us to investigate for the realistic heterogeneous behavior of the operators in the telecommunication market, which we assume, may be driven by the heterogeneous potential of operators.

Remark 10. *The analysis also confirm the correct implementation of the simulation setup.*

3.11.2 When the Operators Have Heterogeneous Potentials

This configuration can be translated as the environment where the operators have different costs slopes (private valuation of the user requests) for different users and services. In this configuration, the two operators target heterogeneous market with respect to the user types distribution in the common user pool. The operator performance over market can be translated from the offered cost slope values. In the simulation, we assume that operator 1 cost slopes for *good* and *excellent* type users are $\alpha_{operator1,good} = 1.3$ and $\alpha_{operator1,excellent} = 1.2$ respectively, whereas operator 2 offers $\alpha_{operator2,good} = 1.6$ and $\alpha_{operator2,excellent} = 0.8$ cost slopes for *good* and *excellent* type users respectively. Given these simulation settings, we investigate the performance of proposed network selection approach in the heterogeneous simulation configuration for different performance evaluation parameters (Similar to those investigated in the homogeneous configuration). Fig 3.13(a) represents the amount of accepted requests of both user types. As can be seen that operator 2 accepts 25% more good type users and accepts 31.3% less *excellent* user type requests when compared with the operator 1. The results confirm the operators' preferences over the target market segment i.e., operator 1 targets both the user types. This argument is justified by the fact that the amount of accepted calls of both the user types by operator 1 fall in the close proximity to each other (e.g., operator 1 accepts 120 *good* type requests and 102 *excellent* type of users). Similarly operator 2 targets the good type users more (e.g., operator 2 accepts 148 requests of *good* type of users and 70 request of *excellent* types of users).

We now study the blocked calls due to higher service costs for both operators in the heterogeneous configurations. The curves in Fig 3.13(b) represent the results, as can be observed from the figure that operator 1 accepts 25.2% more requests of good type users. This behavior is justified by the configuration settings, where the operator 1 focuses more on winning the *good* type users, this argument is further strengthen by the curves representing the blocked calls by operator 2 for the *excellent* type user requests, where operator 2 blocks 32% more calls than that of operator 1. We also investigate the user perceived QoS in this configuration. The arguments presented for the perceived QoS in the homogeneous configuration also hold here and the results for user the perceived QoS are depicted in Fig 3.13(c). The call blocking in heterogeneous configuration is shown in Fig 3.13(d), as evident from the figure that operator 1 blocks 8.5% more requests of the *good* user types. However, the reduction of 7% is observed in call blocking of operator 1 for *excellent* type users. We also investigate the operator's rev-



(a) Accepted calls by both the operators

(b) Operators' lost bids for service requests of different user types

(c) User perceived QoS for different extended services

(d) Blocked calls due to scarce radio resources

(e) Operators' revenue

Figure 3.13: Performance analysis of proposed approach in heterogeneous settings for different performance evaluation parameters

enue in this configuration. As can be seen in Fig 3.13(e) that operator 2 increases its profit in the good type users, whereas operator 1's profit comes from both types of users. These curves justify the earlier mentioned claim that cost slopes (operators' private valuation) proves to be a controlling lever through which operators define their preferences over the target user type(s) segments of the common user pool.

3.12 Results and Analysis (In case of event based network selection)

By event based network selection configuration, we mean that the network selection decision is triggered everytime any of the considered evaluation parameter(s) drops below some predefined threshold value, which may be generic for all user types or varies with respect to user types. However, this is typically dependent on the parameter(s) under consideration. In this section, we do not only analyze the event based network selection (using proposed utility function presented in chapter 2), but also study the users' gain in terms of individual QoS metric (e.g., delay, jitter, and packet loss, etc.) and service charges. We also compare the performance of the proposed approach to the other approaches. In this simulation settings, we take an opportunity to study the performance of proposed approach in multioperator integrated HSDPA and WLAN architecture. In this connection, we implement the simplified HSDPA model.

3.12.1 Simplified HSDPA Model

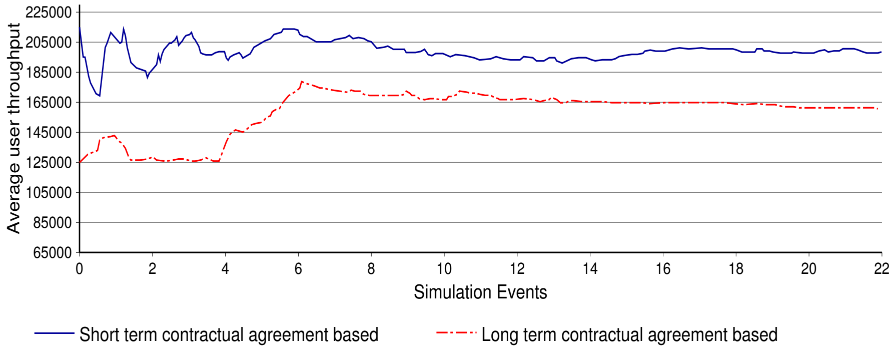
The goal of this model is to hide all complicated details of access technology and focus on throughput achievable at application layer in a particular situation. In our HSDPA model a transmission time interval (TTI) of 10 ms is assumed. Data for downlink transmission for each MN is held in a buffer associated to a particular QCI (Quality Channel Indicator). MAC scheduler schedules two MNs in one TTI. Transport block size for each scheduled MN in a TTI is computed as follows:

- As the first step total signal attenuation of the selected MN is computed. Total signal attenuation is computed as the sum of two parts i.e., pathloss and shadowing.

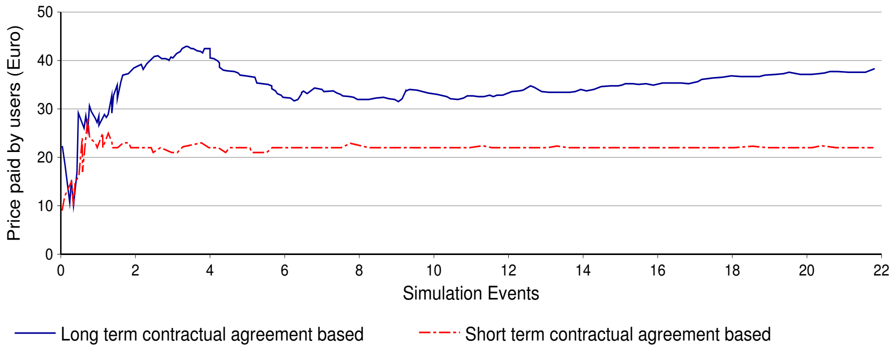
  Pathloss - It is signal attenuation due to distance between nodeB and MN. COST231 WalfischIkegami model (97) provides following relation for this purpose

  $$L_{dist} = 35.5 + 30logf + (-4 + 1.5(\frac{f}{925} - 1))logf + 38logd \qquad (3.14)$$

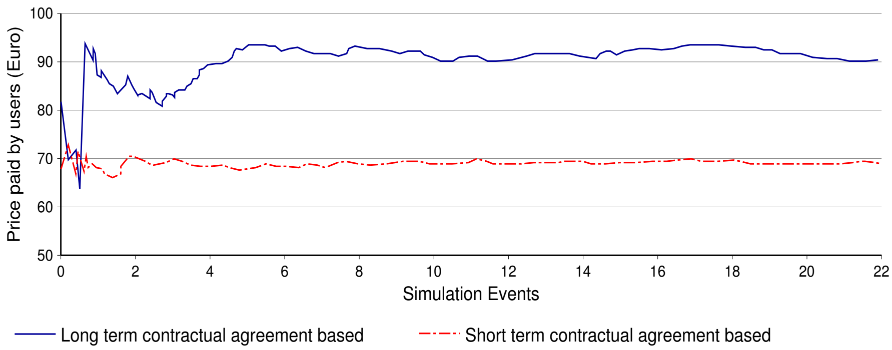
  where f = 2000 MHz and d is distance from cell antenna in meters.



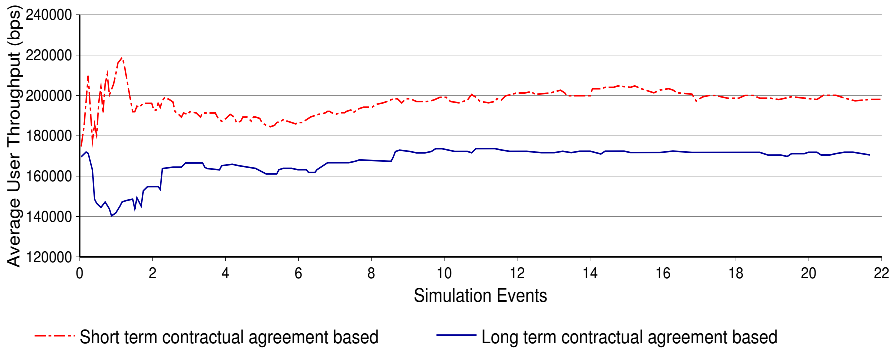
(a) Throughput Comparison(basic user of op-1 in LTC)



(b) Cost Comparison(basic user of op-1 in LTC)

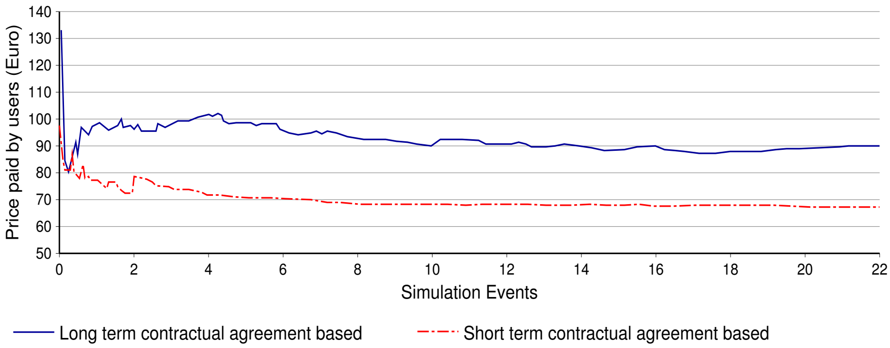


(c) Throughput Comp(premium user of op-1 in LTC)

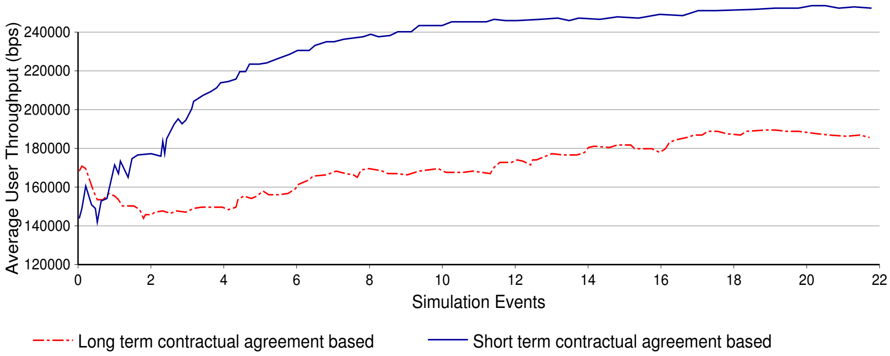


(d) Cost Comparison(premium user of op-1 in LTC)

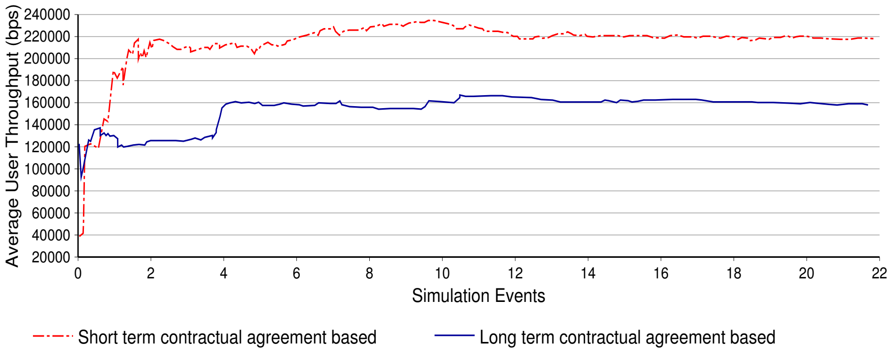
Figure 3.14: Throughput, cost comparison of different users in LTC and STC settings (Operator 1)



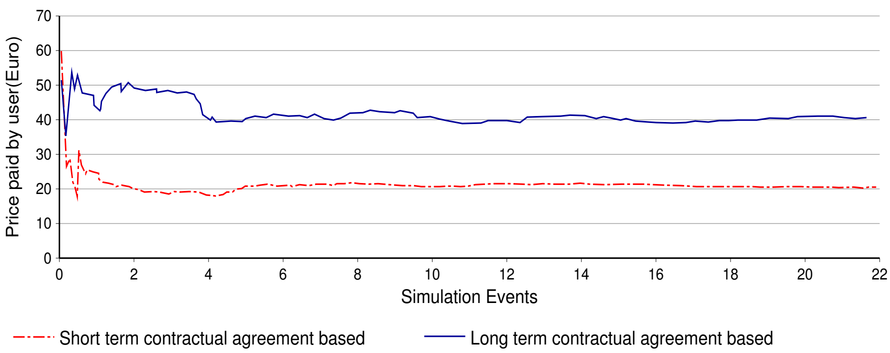
(a) Throughput Comp(premium user of op-2 in LTC)



(b) Cost Comparison(premium user of op-2 in LTC)



(c) Throughput Comparison(basic user of op-2 in LTC)



(d) Cost Comparison(basic user of op-2 in LTC)

Figure 3.15: Throughput, cost comparison of different users in LTC and STC settings (Operator 2)

Shadowing - It is signal attenuation due to presence of buildings and other objects between MN and cell antenna. According to (98) it can be assumed to be lognormal distributed with mean 0 db and standard deviation

$$f(x; \delta, \sigma) = \frac{1}{x\sigma\sqrt{2\Lambda}} e^{\frac{(ln(x)-\delta)^2}{2\sigma^2}} \tag{3.15}$$

For $x > 0$, where δ and σ are the mean and standard deviation of the variable's natural logarithm

- The range of total signal attenuation value is mapped linearly against CQI value range(130)
- Transport block size is looked up against CQI value for MN categories 1 to 6 (99)
- In one TTI a scheduled MN receives 15 transport blocks of data
- Code rate Rc = 1/3 is considered to compute total number of bits to be transmitted for a scheduled MN, BLER = 1% is considered to include error rate in transmissions

3.12.2 Simulation Settings and Analysis

It should be noted that the simulation settings remain the same except for replacing the LTE access network with the HSDPA access network technology. The radius of HSDPA is set to 500 meters and shaping rate of 2Mpbs. We compare the performance of the proposed Short Term Contractual (STC) user centric approach to the Long Term Contractual (LTC) approach. Users generate the FTP requests of 1Mbytes file, the inter-request arrival time is exponentially distributed with the mean 20sec. In this setting operator 1 offers comparatively lesser prices than operator 2, operator's behavior on offered prices remain the same during both STC and LTC simulation settings. Such setting enables us to observe the change in operators' revenue and users' churning out behavior to the lower cost option i.e., operator 1. The simulation is run for 80000 rounds for both STC and LTC settings.

In the Fig 3.14(a),3.14(b), we analyze the gain of *good* user types in terms of throughput and the price the user is charged for the extended services. As can be seen that results present the comparison of the proposed STC based approach against the LTC based approach. When considering the LTC setting, the user under consideration belongs to operator 1. It can be observed from the curves that our approach out-performs the LTC based approach both in in terms of user throughput by 25% increase and 39% decrease in terms of user paid price. We now investigate the performance of our approach for *excellent* user of operator 1 on the

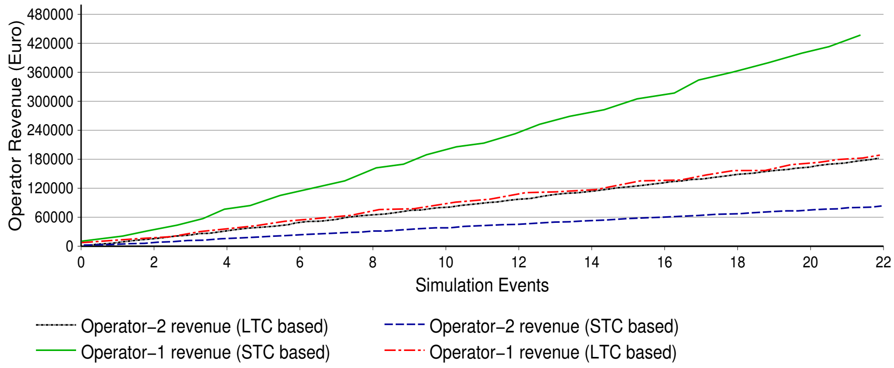


Figure 3.16: Opertor-1's revenue comaprison in LTC and STC setting

same lines in Fig 3.14(c),3.14(d), an increase of 23% in throughput and decrease of 17.6% in price is observed. Similarly an increase of 24.4% and 37.5% in throughput, decrease of 40% and 50% in price paid by *excellent* type users and basic users of operator 2 are observed in Figures 3.15(b),3.15(c),3.15(a),3.15(d) respectively. Fig 3.16 reveals that operator 1's revenue is increased by 150% in STC simulation settings, when compared with LTC settings. Whereas operator 2 looses 54% revenue in STC simulation settings as shown in Fig 3.16. This is due to higher churning out rate of users to operator 1. In LTC settings operator 2 earns more owing to the users' compulsion of being associated with it, even if operator-1 is offering more attractive offers in terms of prices, as shown in Fig 3.16. To further strengthen this observation, we also analyzed the call blocking probabilities of both the operators with varying number of associated users. It is observed that in STC settings operator 1 gets into congestion and blocks calls earlier owing to higher resource utilization and larger user pool.

Remark 11. *If the decision of network selection is based more on dynamic parameters e.g., the decision is triggered by a slight variation in the delay value. Intuitively this solution poses the problem of frequent network switching and potentially causing a ping-pong effect in interface selection. This further dictates that handover frequency may be reduced by basing the handover decision over the less dynamic parameters.*

Considering the Remark 11, one can easily notice that the proposed network selection is based on the MOS value (i.e., user type), which is less dynamic when compared to the most commonly used QoS parameters like delay, packet loss and jitter. This comment is justified by the transforming the network QoS indices into MOS values (specifically for NRT applications) as shown in section (refer the FTP application section in Chapter 2). Hence decrement in the handover frequency is expected. In this connection, we analyze the results in Fig 3.18, where we compare the handover frequency of the proposed MOS based approach against the handover frequency of the network QoS indices based approach (the indices approach, where the decision mechanism is triggered when any of the considered QoS parameter drops below some threshold). As can be seen in the Fig 3.18 that the proposed approach consequences in very small number of handovers when compared with network QoS indices based approach and still fulfills the user QoE requirements i.e., the achievable throughput of user remains within the bound defined by the user type. The result advocates the superiority of the MOS based approach.

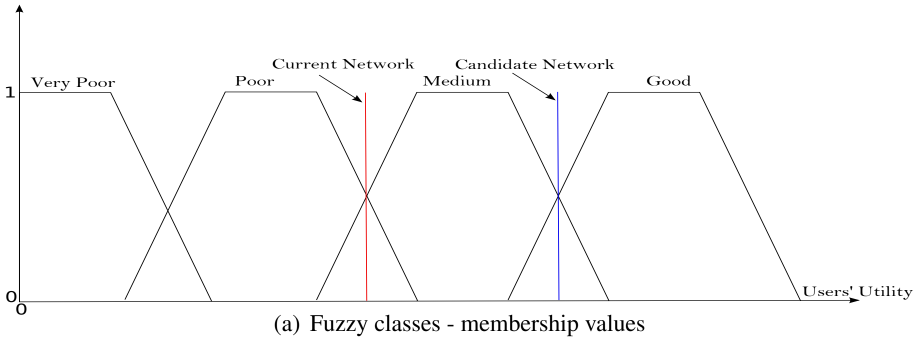
In order to address the higher handover frequency issue and reduce the ping pong effect, we also make use of another approach, the *fuzzy logic* approach (100). In this context, we first map the network conditions (that are translated into utility function of users) to fuzzy input values. We take four membership values namely i) very poor, ii) poor, iii) medium, iv) good as detailed in Fig 3.17(a). The fuzzy input can take any value of a membership class from $0 \sim 1$ due to the slope with finite gradient. Consider the *current* and *candidate* networks depicted in Fig 3.17(a). The utility of a user for these two networks is expressed as in Table 3.5.

Table 3.5: User utilities for the networks in Fig 3.17(a)

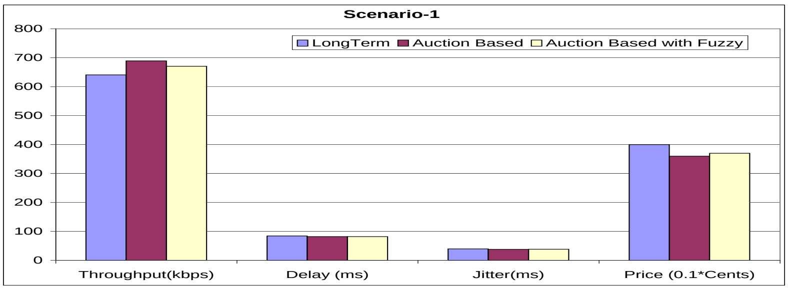
Networks	Very poor	Poor	Medium	Good
$(\bar{w}, o)_{\bar{w}\in W, o\in O}$	0	0.5	0.5	0
$(w, o)_{w\in W, o\in O}$	0	0	0.5	0.5

The decision of handing over to the candidate network technology in the depicted case is positive, i.e., $0.5 + (-0.5) + 0.5 + 0.5 = 1$. Therefore, user gets associated with the candidate network. However increasing or decreasing the number of membership values influences the behavior of users' handover decision. The more the membership classes are the more sensitive user is to the decision metric values. This is illustrated in Fig 3.19(c) and Fig 3.19(d), where for almost similar simulation settings different membership values are considered and its effect on number of handovers is analyzed. An improvement of almost 31.9% over the number of handovers is observed for a cost of 3% throughput degradation, which outperforms the other approaches discussed later in this section.

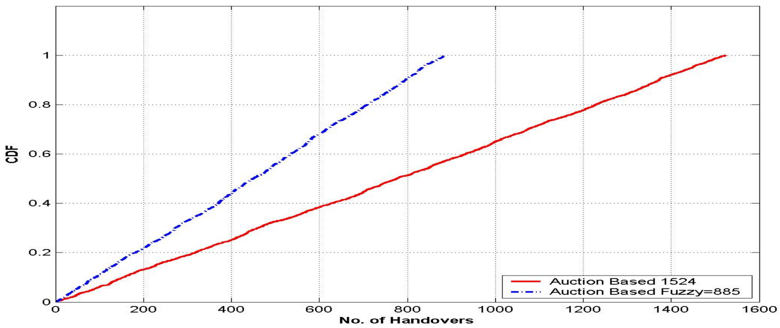
Average values over user's throughput, delay, jitter, packet-loss and payed price over 5000 decision instances are depicted in Fig 3.17(b), which reports an improvement of about 10% in



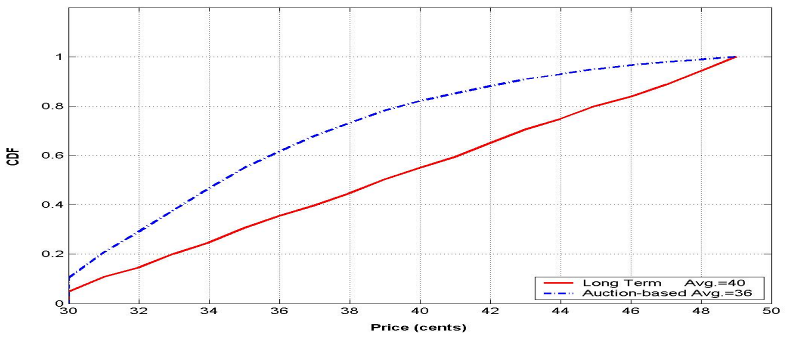
(a) Fuzzy classes - membership values



(b) Comparison of proposed approaches in terms of throughput, delay, jitter, and price that users pay against the long term and other approaches.



(c) CDF curve for number of handovers



(d) CDF curve of price

Figure 3.17: Comparison of different approaches

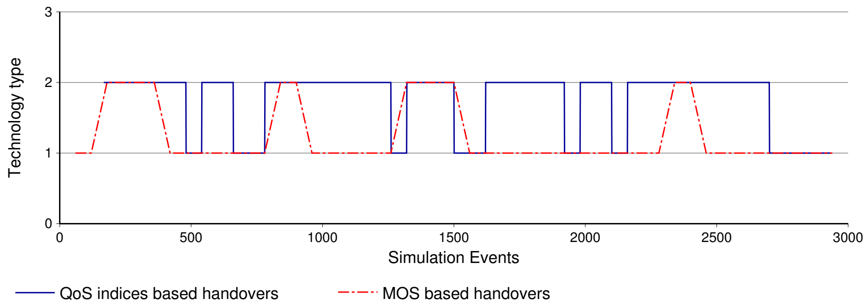


Figure 3.18: Comparison of MOS based QoS indices based handover triggers - In this analysis we configure the simulation setup such that QoS indices tirgger include packet loss values i.e., when the packet loss goes above 2%, the handover is triggered. On the similar lines the handover is triggered, when MOS value drops below some threshold. Such MOS threshold value when translated in throughput values turns out to be 80kbps - 100kbps, thus throughput when drops below the threshold value, the handover is triggered. It can be viewed that using the MOS value approach the handovers frequency is reduced by greater amount.

user throughput and about 9% in price for the *auction-based* approach. Intuitively our *auction-based* approach can perform even better if we relax our strict assumption of operators' ability to meet users QoS requirements. The improvement is achieved at the cost of frequent handovers, which is revealed by the Cumulative Distribution Function (CDF) curve in Fig 3.17(c). To achieve a tradeoff between handover frequency and ABC goal, we also simulate *auction-based with fuzzy* approach. Fig 3.17(c) depicts that in terms of both throughput and price *auction-based with fuzzy* approach performs almost the same as *auction-based* approach, but with almost halved handovers. Fig 3.17(d) presents an additional comparison over the price with the CDF curve.

Moreover, besides the *Auction-based* and *Long-term-based* network selection schemes, we consider an additional user-centric approach termed as *RSS-based* scheme, where users can connect to the best available network based on the received signal strength (RSS) value. We assume that all users follow a trajectory starting from the same point in a simulation area of $62 \times 42km$ with randomly generated network technologies of different characteristics owned by different operators. The simulation scenario results in number of abstract coverage areas, where we investigate the behavior of different types of network selection schemes for the same set of requests. Fig 3.19(a) reveals that *auction-based* and *auction-based with fuzzy* schemes outperform other approaches both in terms of user's throughput and the price the user pays for the service. User's throughput in auction-based is superior by 11% and 11.4% compared to *long-term-based* and *RSS-based* approaches, respectively. Similarly *auction-based* and *auction-based with fuzzy* incur about 10.2% and 7.7% less cost when compared with the *Long-term based* approach. The prices in the *RSS-based* approach are almost similar to those in *long-term based* approach. CDF curves in Fig. 3.19(b) provides a deeper insight in this respect.

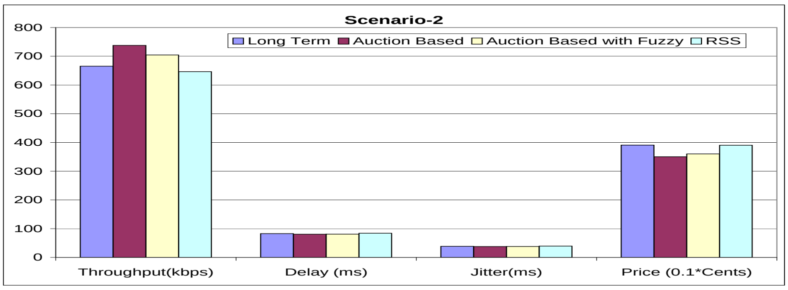
Fig. 3.19(c) details that the number of handovers in *auction based* approach is reduced by almost 29% in *auction-based with fuzzy* approach. However, the other approaches result in fewer network switches, which is self explanatory on account of compromise on price, throughput and user preferences.

A set of simulations using the similar settings with modified fuzzy settings is carried out to analyze the effect of fuzzy approach on the number of handovers. Less number of membership values reduces the handovers by an appreciable amount. Fig. 3.19(d) shows an improvement of 31.9% in terms of handovers at the cost of 1.8% throughput degradation when compared with fuzzy auction-based scheme with greater membership values as shown in Fig 3.19(c).

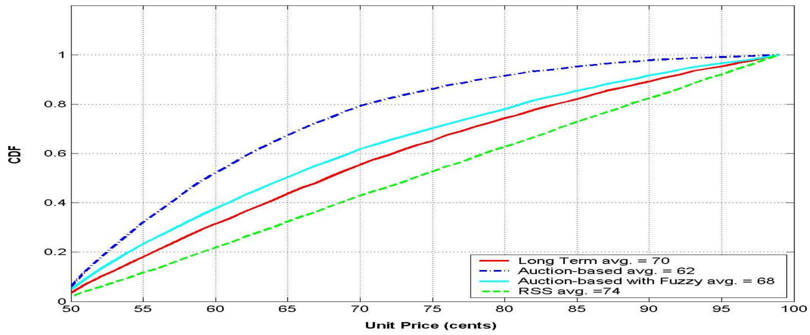
In the light of discussed results, we can comfortably claim that the proposed user-centric entwork selection approach out performs different approaches in terms of user perceived Qos, operator revenue, call blocking, and resource utilization. Thus proves to be a candidate solution for realizing the envisioned user-centric network selection vision.

3.13 Conclusion

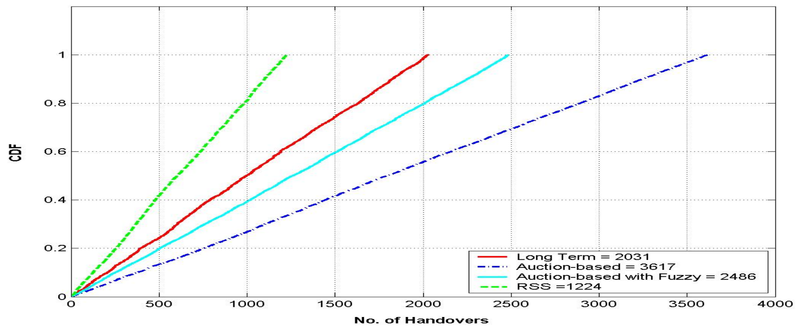
In this chapter, we proposed the auction based user-centric selection approach and discussed the architectural realization solutions for both the intra and inter-operator configurations. The interaction among architectural entities is modeled at the granule level. In order to evaluate the performance of the proposed network selection approach. We compared the proposed approach against various approaches and investigated the gain of the proposed approach in terms of user-perceived QoS, achievable throughput, call blocking, operators revenue, user costs over the services, etc. We observed that the proposed solution outperforms the other approaches. We also discussed the issue of frequent handovers in the user-centric network approaches. We discuss the proposed approach consequence in the reduction of such ping pong behavior by introducing i) MOS based handover and fuzzy logic, ii) We observe that handovers have reduced to an appreciable extent.



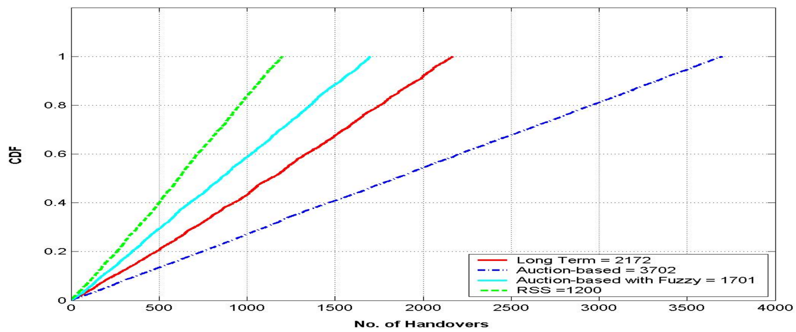
(a) Comparison of proposed approach in terms of throughput, delay, jitter, and price that users pay against the long term and different approaches



(b) CDF curve for price the user pays for the service.



(c) CDF curve of number of handovers



(d) CDF curve of handovers with modified fuzzy membership values

Figure 3.19: Comparison of different approaches

4

Multi-tier Resource Allocation and Network Selection

In future wireless networks, we envision a more dynamic telecommunication paradigm, where the dynamics may be translated into dynamic service offerings and user profiles, etc. We further expect that the wireless communication markets will be influenced when the user-centric network selection vision is realized. This dictates that operators will compete for their share of a common user pool on much smaller time quanta when compared with the current long term user contracts with the operators. One intuitive strategy of operators in such a configuration will be to incentivize users by offering different QoS and the service price offers. As the operators' offers are influenced by their incurring costs, thus it provisions the study of the market behavior at different levels and investigate the operator and user behavior at these level. This chapter focuses on a bigger picture involving more wireless communication players e.g., spectrum brokers (traders), network providers, new entrants, users, and service providers, etc. We model the interaction between different players and investigate their strategies. We categorize, position the communication players and model the interaction between players at different levels. We introduce the learning aspects in the interaction and investigate the equilibrium strategies of involved stake-holders and model the utility functions of all the involved stakeholders. We also examine the risk-sensitive utility functions in order to cover both risk-seeking and risk-averse in the user QoEs.

4.1 Introduction

The scarce radio spectrum turns out to be the main pillar to the future wireless communications. The spectrum management in any country is regulated by the a governmental body (e.g., FCC in USA or ECC in Europe). The current trend of spectrum allocation is derived by the concept of *rigid frequency distribution* through auctioning. Such allocations are static and specific to usage parameters (i.e., power, geographical scope, etc.) and usage purposes (i.e., cellular communication, TV broadcasting, radio broadcasting, etc.). Although auctions have been a success in this regard by putting essential spectrum in the hands of those who best value it and generating competition among the operators, such spectrum management may not cope up with the growing needs of spectrum with the user-centric approach in place and the presence of various small scale new entrants e.g, MVNOs in the wireless market. We now briefly discuss the inefficiency introduced by the current fixed spectrum allocation market trends. The telecommunication operators bid for the amount of frequencies they are interested in, if declared winner, the bidding operators are allocated with some amount of frequencies for the periods spanning over years. This fact dictates that the operators frequency demands are the result of their peak traffic planning i.e., *busy hour*, which represents the peak network usage time. It should be noted that bandwidth demands are exposed to variation not only with respect to time (temporal variation) but also depends on the location (spatial variation). This, in a way addresses the issue of satisfying the operators' demands and reducing the call blocking at the operator end, however it causes temporal underutilization in less busy periods. Hence the static spectrum allocation often leads to low spectrum utilization and results in fragmentation of the spectrum creating "white space" that cannot be used for either licensed or unlicensed services. The other good reasons for inefficiency of the current static frequency allocation regulation include that owing to the capital intensive governmental licences, the business opportunities are limited to giant operators. Furthermore, the spectral and spatial restriction on frequency re-usage due to rigid interference handling policies exclude many potential frequency exploitation opportunities. The objective of improving spectrum utilization and providing more flexible spectrum management methods can be achieved by the currently well known concept, DSA.

DSA can significantly improve the spectrum utilization and provide a more flexible spectrum management method and promises much higher spectrum utilization efficiency. DSA concept brings a good news for the wireless service providers, as the flexible spectrum acquisition gives a particular provider the chance to easily adapt its system capacity to fit end users' demands. One could wish for situations, where solutions are not accompanied by the issues, the DSA solution also brings few challenges e.g., frequency interference problem and DSA implementation in user-centric wireless communication paradigm, etc. In this chapter, we confine our discussion more on DSA in user-centric paradigm, the interaction of stake-holders in the mentioned paradigm, and the related issues. Obviously the DSA problems turns out to be more complicated, when it comes to user-centric network selection scenarios, where the user pool is dynamic, in this case the operators are faced with two obvious competitions. We term these competition with respect to their positions in the wireless communication hierarchical figure i.e., Fig 4.1. The competition or the interaction that takes place vertically above the operator level is termed as *upstream competition*, competition on the similar level is termed as *horizontal competition*, and the competition vertically downwards is termed as *downstream* competition. The details of these competitions are provided later in this chapter. Our focus in this chapter is to capture the the interaction among spectrum holder, wireless service providers and end users. Intuitively all the stake-holders in this scenario aim at maximizing their own profits. We formulate wireless service providers' competition for spectrum and user pool portions in the different markets. We investigate stability of all the markets and evaluate market efficiency of the equilibrium.

4.2 Motivation

The hierarchical wireless communication model presented in Fig 4.1 dictates interdependency of the stake-holders i.e., the stake-holders at the operators level depend on the service demands pattern from underlying common user-pool for formulating their (operators) spectrum demand at different times and for different geographical locations. The service demands do not only influence the operators spectrum demand but also the operators' valuation for the spectrum. On the similar lines, the offered service pricing and service quality by the operator drives the user demands, which in turn has impact on the spectrum demands (as stated earlier) and consequently the profit of spectrum broker and stake-holders at the operator level. Such dependency of stake-holders produce different markets (We will explain these markets later in this chapter). Thus capturing the efficiency (e.g., resource utilization at operator level, user satisfaction maximization at user-level, etc.) at one of the hierarchical levels and not considering their dependency on the other levels may not lead to realistic efficient solution. We also note that the recently presented DSA solutions lack the consideration of some key issues. Such as the interaction among the different frequency leasers specially when it comes to the mix of MVNO and network provider type of operators, where these operators differ in their incurring costs, such interaction may also include information about noise and frequency interference among the stake-holders. Considering the future user-centric wireless network paradigm, the characteristics of attractive LTE like technologies, and the interaction among all the stake-holders, one can think of a more realistic spectrum distribution or we emphasize more on naming this as the spectrum trading at the operator and spectrum broker level. Modeling the interaction and markets at the operator, modeling the co-existence of new entrants and the incumbent operators so that the potential of market for both the stake holders is clearly defined. We are also convinced that the interaction model is different for different geographical regions, hence there is a need for a generic model that captures the interaction for the regions and define all the markets on granule level. In the current literature these aspects are widely oversimplified and many frameworks have been presented lacking to fulfill the basic requirements of general distribution systems, where limited resource is to be divided among the participants. Although the existing literature that discusses the possible spectrum allocation models and related issues is vast, our work focuses on modeling the interaction at different levels, where the interacting entities are different in their characteristics. We investigate the equilibrium strategies at different hierarchical levels presented in Fig 4.1.

We also take an opportunity here to justify the technical feasibility of dynamic spectrum allocation concept i.e., new generation radio interfaces support flexible transmission frequencies. The trend of future wireless technologies promises to ensure the user satisfaction for the envisioned dynamic bandwidth hungry service e.g, LTE is expected to deliver five to ten times greater capacity than most current 3G networks with lower cost per bit. LTE also promises the flexible operational frequencies. Future wireless network communication is boosted by the concept of technology virtualization. When it comes to technical realization of the dynamic spectrum allocation concept, one of the attractive solutions is *virtualization*. The choice of *Virtualization* as a technical solution is driven by the widespread and yet growing presence of this concept in the research literature e.g., many research projects including PlanetLab and GENI (101) (102) in the United States, AKARI (103) in Asia and 4WARD (104) in Europe. An interesting fact is that virtualization itself is not new and has been known and used for many years, for example virtual memory in computers had already been used in the early sixties. So the natural question one may think of is: *What makes an old technique still appealing today?*

The answer to this question is not straightforward and provisions a review of the technical advances over the last five decades. We know that the consequence of the technical evolution over half a century is; a huge process power (even in commodity hardware), endless cheap storage (Terra-bytes), etc. Thus the evolved technical environment is equipped with machines, whose resources are not fully utilized and can be shared with other entities and processes (which require resources), this argument forms the basis for the growing importance and existence of virtualization in the time to come. There is a number of research activities in virtualization as well as a number of commercial solutions using virtualization: e.g., Server Virtualization, Router Virtualization, XEN, Cloud computing, etc. It was evidently obvious that the next step is to try bringing virtualization into the network as a whole and to combine all of the different virtualization research activities into forming what is known as “Virtual Networks” or “VNets”.

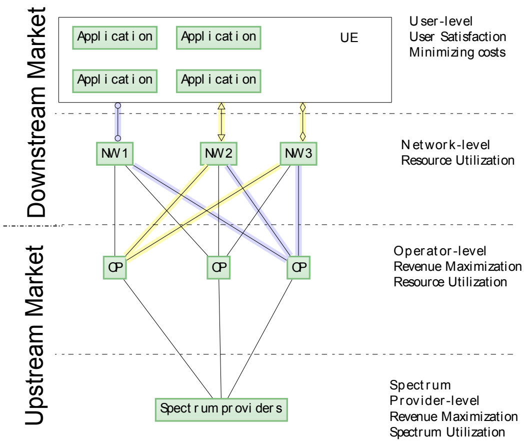


Figure 4.1: Hierarchical position of telecommunication stake-holders and their objectives - In the figure four different hierarchical levels are shown, on each level the telecommunication stake-holders are positioned. The positioning of telecommunication stake-holders is influenced by their functionalities and interdependencies. On each level the objective function of stake-holders are also listed.

Wireless virtualization is yet another very important aspect specially for the future wireless networks. The best candidate for applying virtualization in the wireless domain is mobile networks. Mobile networks are the fastest growing networks globally and one of the biggest players in the future. In (105), it was shown that virtualization in mobile networks (represented by the LTE) has a number of advantages. Multiplexing gain as well as better overall resource utilization were the key gains achieved. In (106), a more practical framework was investigated for LTE virtualization and spectrum sharing among multiple virtual network operators. The framework focused on a contract based algorithm to share the spectrum between the operators. As stated earlier that future wireless communication market will be open for the small scaled new players. For instance MVNOs, who focus more on customers, community and content rather than technology, thus not necessarily holding the infrastructure resource. This dictates that resource trade is a promising solution for efficient resource utilization.

4.3 Contribution

In this work, we study the wireless market behaviors at different hierarchical levels (of Fig 4.1) specifically in terms of spectrum trade, utilization, and user QoE. The interaction among different stake-holders is modeled using game-theoretic approaches. We categorize and differentiate the interaction between stake-holders based on the point of their existence in the communication chain hierarchy. In the first place, we assume that stake-holders at the operator level may acquire different amount of frequency channels at different times. Thus the spectrum broker follows the allocation strategies that increases its profit function. The interaction between operators and stake-holders at the operator level is modeled using auction-theoretic approach to find the optimal allocation and unit price of the allocated spectrum. We also capture the user-operator level interaction using game-theoretic approaches. We also highlight that users' objective is defined as their perceived QoE and the objective of stake-holders at the operator level include maximizing the resource utilization and profit maximization, which in user-centric paradigm is achieved by increasing satisfied user pool. In this interaction, we concentrate on dynamic price and service quality offers by the operator. Given this scenario, we model the competition between the operators. It should be noted that stake-holders at the operator level exhibit different potentials [1]. Thus we investigate the equilibrium price offer and service quality offer, where no provider finds it beneficial to change the offer unilaterally. Our main contributions in this chapter may be summarized as follows:

- We propose a dynamic spectrum allocation and management framework.
- We model uniform price auction at the spectrum broker and operator level, which dynamically allocate spectrum resources to network provider and MVNOs.

[1] By the operator potential, we man the strength of operator with respect to its technical equipments installations.

- We also suggest the technical realization framework for the interaction of spectrum broker and operators using LTE virtualization.
- We model the horizontal interaction at the operator level between heterogeneous potential operators. We investigate the strategies of both the operators and provide the equilibrium strategies of both the operators.
- We model the spectrum estimation at the operator level in the user-centric network selection scenario.
- We model the operators' private valuation of the spectrum at the operators' level.
- We provide a conflict and decision model under incomplete information game situation. We make the use of the proposed user's utility (user utility function proposed in Chapter 2) and propose the utility functions for both types of the operators (MNP and MVNO). We also investigate existence of Nash equilibrium and propose the service quality offering and service pricing policies that help both the stake-holders at the operator level and users to maximize their utilities.
- We provide simulation results using OPNET simulation by virtualizing the LTE network technology.

4.4 Related Work

Several research contributions on meeting user QoS and bandwidth requirements are present in the literature e.g., (32, 107, 108, 109). These contributions fall under the category of user level of wireless communication hierarchical figure (Fig 4.1). Moving a step ahead, there are a number of research contributions e.g., (110, 111, 112, 113, 114) in the direction of network selection based on various approaches such as fuzzy logic based and policy based, etc. However, most of the research literature either formulate the network selection problem as a static optimization problem or it theoretically assumes that user satisfaction function for any application follows some function (e.g., sigmoid, cobb-douglas curves, etc.), and these assumptions are not supported by the validation that represents the realistic user satisfaction. For more research literature in this direction readers are encouraged to refer to Chapter 3.

Similarly, when it comes to the operator level interaction various competitive and cooperative game theoretic models can be found in the research literature e.g., (115, 116, 117). A parallel development in communication industry is emergence of the concept of network sharing (118, 119), where operators share RANs to leverage investment, and to improve utilization of their investments. This however necessitates the extension of the concept of Common Radio Resource Management (CRRM) to multi-operator scenarios, as well as resource allocation in such scenario is operator's subject.

On the similar lines, we detail the research literature in the direction of DSA as follows; The concept of DSA first came up in the Defense Advanced Research Project Agency nextGeneration (DARPA XG) program (120), the project aims to develop, integrate, and evaluate the technology. The emphasis is on the enabling the user equipment that automatically selects spectrum and operating modes to both minimize disruption of existing users, and to ensure operation of U.S. systems. In (121), the authors propose a spectrum broker model that controls and provides operators the time bound access to a spectrum band. The authors investigated spectrum allocation algorithms for spectrum allocation in homogeneous CDMA networks and executed spectrum measurements in order to study the realizable spectrum gain that can be achieved using DSA.

The authors in (122) propose a scheme where the spectrum manager periodically allocates short-term spectrum licenses. The spectrum rights are traded amongst the operators for a fixed amount of time, the license for the allocated spectrum automatically expires after the predefined time period. However, (123) assumes that the operators follow the multi-unit auction format for the spectrum trade, where the sealed bids are submitted for the spectrum resources and the winner operator pays the second highest price (the price of resource is assumed to be charged on per unit basis). Buddhikot and Ryan (124) in their seminal work discuss the DSA management, where the authors focus on spectrum allocation and pricing. The paper introduces the concept of coordinated DSA and the spectrum broker, the paper also illustrates over various allocation algorithm types e.g., online vs. batched, in addition it also highlights the notion of interference conflict graph, and the cascading effects among brokers on blocked list. Linear programming formulation is used to solve the problem of the spectrum allocation with feasibility constraints i.e., maximal service vs. minimal interference, maximal broker revenue vs. max-min fairness.

In (125), the authors present bidding framework, where the spectrum manager / broker tries to maximize its revenue, moreover, the authors claim that the proposed bidding framework is equally suitable for heterogeneous channel and general complementary bidding function. The paper also presents greedy algorithms with the approximation bounds to solve the NP-hard allocation problems. The authors in (126) argue that the widely employed interference modeling (pairwise conflict graph) is weak and suggest the methods as to how to drive the interference model from the physical interference models so that it produces near-optimal allocation. Zheng et al. (127) use VCG format of auction to model the spectrum allocation problem. A distributed algorithm for spectrum allocation by the local coordination through bargaining is suggested by (128), where the users are assumed to cooperate with a common objective of increasing the social welfare, defined on spectrum utilization and max-min fairness, which dictates that user selfishness is not considered, the authors take care of interference by introducing the conflict graph approach. The authors extend their work in (129) and investigate the efficiency of their proposed scheme in terms of its convergence time and communication overhead, and deduce lower bounds on system performance characteristics including fairness level, and upper bound on complexity. A deviation from the use of distributed approaches is observed in authors centralized auction based approach (130), where authors assume pairwise interference conflict graph, piece-wise linear bidding functions, and homogeneous non-overlapping channels. Given these assumptions the authors authors formulate the allocation and pricing using the linear programming approach. Authors give the approximation bounds of the proposed heuristics and discuss the trade-off between revenue and fairness. They also argue on the difference between global market-clearing price and discriminatory pricing schemes. (131) relies on the VCG mechanism in a sealed-bid knapsack auction when determining spectrum allocation, but in the presented economic model the authors also account for the interaction between wireless service providers and users, and determine dynamic pricing rules to capture their conflict of interest. On the other hand they do not discuss interference issues. The efficiency of spectrum utilization is also addressed in European Union projects such as Dynamic Radio for IP Services in Vehicular Environments (DRiVE) (132) and overDRiVE (133), that investigates co-existence, sharing rules with broadcast and military systems and scenarios for a dynamic regional/temporal spectrum allocation. The concept of dynamic spectrum trade is further strengthened by invention of software defined radios (SDR) and reconfigurability concepts. However in the DRiVE, overDRiVE and other such research literature, it is assumed that RANs already hold some amount of spectrum, which is traded when needed. However in a scenario, when all the RANs, specifically inter-operator RANs are self sufficient or under-utilized in terms of their spectrum, intuitively no auction takes place. The decision of what amount of spectrum should a RAN /operator have in any geographical region is to be estimated, which turns out to be even more difficult when users have short term contractual agreements with operators.

4.5 Background

In this section, we provide the background knowledge on auctioning format used in this chapter and heterogeneous characteristics of different operator types i.e., MVNO and MNP.

4.5.1 Uniform Price Auctioning

In the uniform price auction a fixed number of identical units of a commodity are sold for the same price. Each bidder in the auction bids a price and a quantity. The price bid is considered as the maximum price that bidders are willing to pay per item, and the quantity is the number of units they wish to purchase at that price. Typically these bids are sealed, not revealed to the other buyers until the auction closes. The auctioneer then serves the highest bidder first, giving him the number of units requested, then the second highest bidder and so forth until the supply of the commodity is exhausted. All bidders then pay a per unit price equal to the lowest winning bid (the lowest bid out of the buyers who actually received one or more units of the commodity) regardless of their actual bid. Some variations of this auction have the winners paying the highest losing bid rather than the lowest winning bid.

4.5.2 Mobile Virtual Network Operator (MVNO)

The definition of MVNO is specific to its characteristics and may take various definitions. Generally from the network perspective, the MVNO is an organization or the firm that extends various telecommunication services to the end users but may not hold license of the radio spectrum. This definition further dictates that MVNOs borrow the resources[1] from the stake-holders (either MNPs or Spectrum Broker (SB)) in any geographical region. One may think of MVNO as the organization that takes the following roles: i) MVNO may own spectrum in one region and borrow the spectrum in another region, ii) MVNO may deploy its own infrastructure that enables it to have better control on offered services. However, when it comes to defining the MVNO from the user or business driven perspective, the MVNO is then defined as an organization that the user believes is its mobile operator, but does not necessarily have to own or manage all or part of the underlying physical network.

[1]Network infrastructure and air-time, the spectrum resource may include CDMA, GSM, LTE, UMTS, HSDPA, etc.

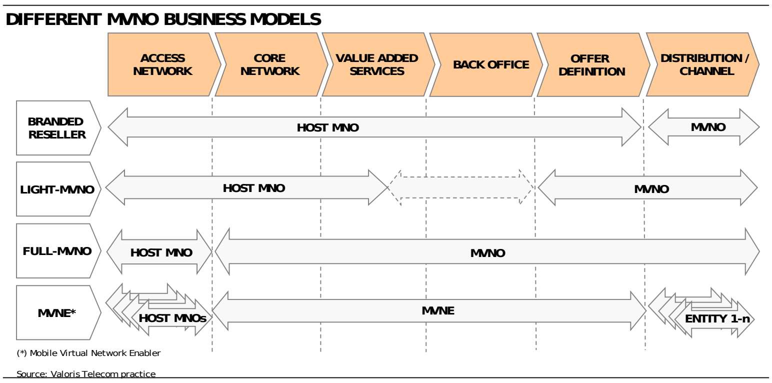


Figure 4.2: Different MVNO Models - This figure illustrates different types of MVNOs and their control on the entities (134)

MVNO can be defined in different scopes as shown in the Fig 4.2, we believe that a careful look at the figure will enable readers to grab the idea of the addressed spectrum allocation problem. Let us define the MVNO on broader scale and take it for an entity that speaks more about customers, community and content than they are technology. Given this definition MVNO's offerings should to be focused on specific class of audiences with a greater emphasis on the customer care component. Although the question, *Whether a MVNO business model is sensible and acceptable to the marketplace?* is regarded as no longer a question,

4.5.3 Mobile Network Provider (MNP)

MNPs e.g., T-Mobile, Vodafone, O2, etc. are the licensed firms to operate their services (currently mobile telephony) over a range of frequencies within the radio frequency spectrum, these licenses are allocated by the country's regulatory authority. Generally it is assumed that a MNP holds the entire communication infrastructure required i.e., hardware and administrative infrastructure. By hardware here, we refer to the communication equipments such as switches, base station controllers (BSCs), Master Switch Controller (MSCs), transmission lines, backbone infrastructure (fiber based, Digital radio system or microwave based), media gateways, etc. By administration we refer to Marketing, Branding, Billing, Operational Support, and Business Support.

4.6 Co-existence of MVNOs and NPs

The motivation to include this section comes from the fact that the reader should be provided with clear differentiation in the characteristics of the considered operator types, we also present the argument for justification of the co-existence of these two operator types.

We study here the necessary conditions for co-existence of MVNO and its network operator partner in terms of their corresponding profits. Intuitively one of the major issues the stake holders (MVNOs or MNPs) consider with any market segment is the risk. The risk is basically scaled with respect to the operators potential in the market. e.g., financial markets are tough on operators if ARPU (average revenue per user) drops, so they cannot take on certain customer bases as a result. The issue is, the large operators are actively chasing markets within their risk threshold, but these operators generally offer *one-size-fits-all* service packages, whereas the future wireless service users are envisioned to be more interested in dynamic and more personal services. This or many other such reasons form basis and justify the co-existence of MVNO with NP. Looking for more reasons to justify the existence of MVNO in the market, we can not forget to mention that building an MVNO provisions enormous amount of cash, to be spent on advertising, partnerships, wholesale network and content services, customer care support and various kinds of software. All that cost is an undesirable burden to an MNO (specifically for targeting niche markets), however at the same time is a key driver for the MVNO's need to become known, access customers, control data, billing and customer interactions.

Currently a great MVNO activity is observed in the mobile marketplace (e.g., see (135)). One acceptable argument is that on the one hand there are situations where players from multiple industries exploit the MVNO model to get revenues from the mobile market, whereas on the other hand many MVNOs enter the mobile market on a *pure voice play* and their service offerings may not be very different than those from traditional mobile operators. The consequence of such a scenario may be decline in the voice ARPU, then in this case MVNOs need to execute effective mobile data strategies and create innovative ways to differentiate their services to high-margin multimedia, location based and mobile commerce services. These arguments clearly indicate that an MVNO usually aim at offering not only voice services but also value-added services (also referred as mobile value-added services), which may be a combination of voice, data, graphics and video information e.g., mobile music, mobile TV, games, ring tones, multimedia messaging, mobile commerce and location-based services. Rephrasing the question of MVNO co-existence with MNP, we can say, *Is it possible to create new revenue strams* *in future telecommunication landscape without being an expert?* Yes, following few essential factors make it possible:

- MVNOs may differentiate themselves with new value-added services orientated around customer choice and a personalized customer experience. For example, Helio a US MVNO now offers its customers GPS-enabled Google Maps, OTA music downloads and exclusive access to MySpace Mobile at no charge.
- Convergence has become new driving force behind the next generation of MVNOs e.g., Virgin Media offers a quadruple play package, combining mobile and fixed line telephone services, broadband / TV.
- On paper MVNOs present operators with a way to realize revenue from spare capacity and target niche markets that are peripheral to their core business. However, supporting MVNOs brings with it burdens and risks for the operators. Qualifying the business cases of potential MVNOs to a network provider can therefore be time-consuming and distracting

For more details on different types of MVNO, readers are encouraged to refer (134). Different to MNPs, MVNOs may have narrower range of service as they focus on a particular market segment. Large corporations, small companies or entrepreneurs can use the MVNO model to reach mobile customers with: i) simple and cheap tariffs, ii) New services, iii) Innovative voice and data proposition. Fixed operators can easily enter the mobile market through MVNO owing to its low CAPEX, no license fee, and no network deployment. Few attractive applications of MVNO include i) providing cheaper long-distance call tariffs, ii) extending cheaper and simple services to prices sensitive customers, iii) providing value added music and audio content, iv) providing mobile banking, call filtering, personalized vaoicemail and online inbox, etc. Therefore, MVNOs in particular may arise from: i) Traditional landline operators planning to add mobile services, ii) Mobile operators planning to enter into international markets, iii) Companies with strong brand names, iv) Companies who could not obtain 3G licences, and v) Companies from telecom, media and internet industries.

4.7 Envisioned Future Wireless Markets

Future envisions dynamic and heterogeneous application services, that provision high throughput and more elastic traffic demands, this results in a varying spatial and temporal service

Table 4.1: Markets in future spectrum allocation scenario

Market	Players	Comments
1	Regulator & Spectrum brokers	out of the scope
2	Spectrum Broker, NP & MVNO	detailed in section-4.8
3	MNP & MVNO	detailed in section-4.10
4	Users, MNP & MVNO	detailed in section-4.10

demands. These pose practical challenges of efficiently utilizing the spectrum available to network providers. However, with existing tradition spectrum management[1], attaining spectrum efficiency remains a question mark. An operator with allocated spectrum on long-term basis faces the situations, where it is under or over-loaded. To maximize the profit, operators trickle down the effects of unused spectral durations and long-term spectrum license fee influences to the users. Future also expects diversified nature of services to meet the user needs of future *everything-communicates-with-everything* vision.

Given the above highlighted challenges, there is a need for shift from traditional spectrum allocation approach to a more dynamic one. Researchers have addressed the problem by suggesting a number of *Dynamic Spectrum Allocation* approaches (as explained in the related work). Telecommunication deregulation further paves the path for new entrants (e.g., MVNO, service provider, etc.) to enter the wireless market, this is an attractive candidate solution to meet the user diversified service demands. However the position of MVNO in the *spectrum broker to user chain* dictates a different decision making process than the network provider and spectrum broker, *Spectrum broker to user chain* is shown in the Fig 4.1. As evident from the figure that MNP provider on the lower stream provides point of attachment to the users, and interacts with MVNO, whereas MVNO provide on the low stream provide interface to users only. On the upper stream MNP only interacts with spectrum broker, whereas MVNO interacts with both MNP and spectrum broker.

A closer look at the Fig 4.1 creates various markets, such as those given in Table 4.1 and represented by the numbers $1, 2, 3$ and 4. We further highlight the markets in the Fig 4.3 (where a represents the spectrum resource access fee and $\tilde{a}$ represents the infrastructure access fee). It should be noted that the discussion over the Market-1 is out of the scope of this work, thus the main focus of this work will be on markets $2-4$. We now detail these markets in detail.

[1] In tradition spectrum management, the spectrum chunks are allocated to a specific radio access technology on long-term basis

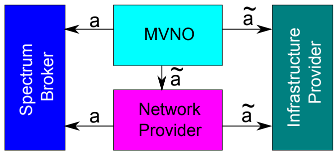


Figure 4.3: Figure representing different markets - As can be seen that the figure depicts various markets e.g., spectrum trade market and infrastructure trade market, etc. The figure highlights incurring costs by different stake-holders in different markets. It should be noted that $a \neq \tilde{a}$, where a represents the spectrum usage charges and $\tilde{a}$ represents the infrastructure costs.

4.8 Upstream Market (Market 2)

It is an anticipated future market, in this market spectrum broker dynamically sells the spectrum resource to the available buyers (MVNO and MNPs in this case). Putting it simpler, a spectrum broker transfers the spectrum usage rights on short term contract (termed as spectrum allocation hereafter) basis to the available incumbent and new entrants when needed. The idea behind introducing this market is two fold. Firstly, it paves path for new entrants to enter the telecommunication market and co-exist with incumbent operators by introducing novel ideas and services. Secondly, making the market more efficient in terms spectrum utilization, hence avoiding the problem of under-utilized periods of the operators. For simplicity, we term both MVNO and MNP as horizontal stake-holders hereafter. In this section, we model the interaction among the horizontal stake-holders and spectrum broker using a well known auction-theoretic approach i.e., uniform price auctions. The basic idea that governs this interaction follows the the concept of *resource trading*, resource in this case is the spectrum. Both sellers and buyers benefit from the auctions in terms of resource utilization and profit maximization. In addition to the contributions presented in the related work, DSA can be found in literature with various regimes and configurations, such as: centralized, distributed, game-theory based, coordinated, and uncoordinated approaches (136),(129),(137),(121), etc. However, most of the approaches do not focus on the practical implementation details of the theoretical solutions. In this chapter, we also present the theoretical approach behind dynamic infrastructure resource sharing, and propose/implement this theoretical approach in a technical framework. Our technical framework is based on the well known concept of *Virtualization*. Table 1.1 summarizes the notations used in modeling the interactions within this chapter.

4.8.1 Assumptions in Market - 2

We assume that the environment consists of a spectrum broker and various MNPs and MVNOs. We further assume that both MVNO and and MNPs provision the spectrum resource on dynamic instances. The spectrum resource is traded between operators and spectrum broker on the need basis. The payment made against the traded resources are based on the "pay-as-you-go" format. In order to capture the demand specific to different services, we differentiate the network operators with respect to service types i.e., each operator is characterized by mutually exclusive service types (this assumption is justified by the arguments presented in section 4.6). The network operators assess their demands and periodically acquire the resource from the spectrum broker. Upon the demand realization, the spectrum broker take decision over resource allocation and the price per unit resource that it charges for the extended or rented resources.

In this environment, we assume that MNP already has some spectrum, which we call the long-term static spectrum allocation. The assumption of holding some amount of static spectrum is realistic in case of existence giant operators, as they already share the market segment for their communication services. However, the amount of static spectrum holding is driven by operator's confidence of winning the some market share in future. It should also be noted that spectrum holding may follow the existing spectrum allocation rules. On the other hand MVNO may not necessarily have any long-term static spectrum allocation (as it is new entrant in the market). The point of interest of this section is the flexibility introduced by the concept of dynamic spectrum allocation in upstream market. Given the DSA enabled upstream market, the discussion can be confined to situations, where MNP needs extra spectrum from the spectrum broker. This introduces MNP's competition with MVNO over the spectrum.

There has been extensive work available in literature in this direction. However, in this work we address more realistic scenario with heterogeneous potential operator i.e., MVNO and MNP. Both the types of stake-holders have various strategies available to them such as different amount of spectrum resource demands and price per unit of resource that these operators are willing to pay against the spectrum resources to the spectrum broker, etc. Our goal in this market is to model the estimated spectrum demands, the private valuation of the spectrum resources by each operator and model the interaction among the stake-holders using auctioning theory. Intuitively, such investigation also focuses on the behavior of price decision by MVNO and MNP (taking into account their incurring costs).

4.8.2 Operators' Utility Function

In this subsection, we define the utility functions of both the types of operators and illustrate their cost components.

4.8.2.1 Mobile Network Provider Utility Function

The network operator utility function is the difference between its total revenue and its cost, however, the cost component turns out to be smaller in value when compared with MVNO, this is evident from the cost components (explanation later in this section). Network provider utility function is given by:

$$R_o := \sum_{k,c} \pi(o,k,c) n_{o,k}^c - a, \tag{4.1}$$

where a represents the spectrum cost component and index o here represents MNP.

4.8.2.2 MVNO Utility Function

MVNO's utility is formulated in the similar way as MNP's utility function, but with different cost components. MVNO utility function is given by:

$$R_o := \sum_{k,c} \pi(o,k,c) n_{o,k}^c - (a + \tilde{a}), \tag{4.2}$$

where $\tilde{a}$ represents the infrastructure access cost component and index o here represents MVNO.

4.8.2.3 Specification of Operators' Cost Components

In this subsection, we illustrate on the cost components of both the operators (MNP and MVNO). This helps in understanding the difference between cost components of the two operators. It should be noted that CAPital EXpenditure (CAPEX) is assumed to be the constant cost and neglected in this work, however we define the costs components in terms of OPerational EXpenditure (OPEX) costs.

- Maintenance of equipments - MNPs mainly incur these costs, owing to the fact that they have infrastructure resources. Such costs are basically *recurring*, *periodic*, and *reparation* in nature. Costs of replacing the outdated equipments is an example of such costs.

- Equipment, software licenses costs - MNPs mainly incur these costs on periodic basis.
- Sales and marketing costs - Both MVNO and MNP incur such costs. These costs are mainly driven by the time period, when a new service is launched. One valid argument may be that the probability of MVNOs incurring such costs more is higher than that of MNPs. This argument is strengthen by the fact that the deriving force for the MVNO's revenue generation is frequently introducing the diversified and dynamic services.
- Customer care - Given the fact that MVNOs comparatively launch more dynamic and supplementary services and are exposed to consumers interface, thus incur such costs more when compare with MNP. The costs incurred on customer services and customer relation management, etc. are the examples of such costs.
- Service management costs - MVNOs incur such costs more, reason being the same as explained for the preceding costs. The activities that incur such costs may include; i) supervision and monitoring of service quality and user satisfaction with respect to service and ii) Service Level Agreement (SLA) monitoring, etc.
- Network management - MNPs mainly incur such costs. The costs incurred on monitoring and configuring the network equipments, etc. are the examples of such costs.
- Transmission links rental costs - MVNOs incur such costs more, as MVNOs do not own any transmission medium infrastructure e.g., leased lines, optical fibers, PCM, Microwave links, or any medium involved in backbone or last mile communication.
- Site rental - MVNOs basically incur these costs. Such costs include the costs incurred on co-locating the communication equipment within MNP physical location.
- Spectrum leasing / trading / license costs - Both MVNO and MNP incur such costs. It should be noted that in this work, we focus on the dynamic spectrum trade. This dictates that the spectrum allocation does not span over the years.

4.8.3 Operators' Private Valuation Price of the Spectrum Resource

We know that both the operators (MVNO and MNP) have private valuation of the spectrum resources, whereas such valuation is influenced by the operators' utility function. In order to compute the operators' private valuation of the dynamically allocated spectrum resources in the upstream market. We observe that each operator can change its parameters of the interactions based on the previous configurations of demands and the previous prices of the other operator.

Denote by π_o be the pricing function chosen the operator o. These pricing schemes induce a reaction at the user level, say, $x(\pi)$. Each operator o anticipates the reaction of users by taking into consideration the fact that its opponent operator has also the prices and QoS offers to the users. Then, the optimal pricing is determined by

$$max_{\pi_o} \; \mathbb{E}_{x\sim x(\pi)} R_o(\pi_o, \pi_{-o}, x) \tag{4.3}$$

At each iteration, the operator observes a numerical value of its revenue and decides to adapt its QoS offers and the associated pricing. To compute the new offer configurations, each operator estimates the spectrum demand based on the previous configuration of the users $x_t(\pi_t)$.

The generic algorithm is described as follows

$$\pi_{o,t+1} = \pi_{o,t} + \hat{\lambda}_{o,t}\hat{d}_{o,t} \tag{4.4}$$

$$\hat{d}_{o,t+1} = \hat{d}_{o,t} + \hat{\nu}_{o,t}\left(\frac{R_{o,t}}{\epsilon_n \xi_n} - \hat{d}_{o,t}\right) \tag{4.5}$$

where $\hat{\lambda}_{o,t}$ and $\hat{\nu}_{o,t}$ are learning rates and satisfy

$$\hat{\lambda}_{o,t} > 0, \; \sum_{t=0}^{\infty} \hat{\lambda}_{o,t} = +\infty, \; \sum_{t=0}^{\infty} \hat{\lambda}_{o,t}^2 < +\infty \tag{4.6}$$

$$\hat{\nu}_{o,t} > 0, \; \sum_{t=0}^{\infty} \hat{\nu}_{o,t} = +\infty, \; \sum_{t=0}^{\infty} \hat{\nu}_{o,t}^2 < +\infty \tag{4.7}$$

$$\tag{4.8}$$

$\epsilon_t > 0, \; \lim_{t\longrightarrow+\infty} \epsilon_t = 0, \frac{\hat{\lambda}_{o,t}}{\hat{\nu}_{o,t}} \longrightarrow 0$, ξ_n is a random variable which takes value in $\{-1, 1\}$. $R_{o,t}$ is a realization of the revenue of operator o at time t.

4.8.4 Estimating the Operator Spectrum Demands

The spectrum demand $D_t(\pi_t)$ is a function of the price proposed by the operators and the associated costs. At market equilibrium, the demand should equalize the supply. The operator estimates the demands in order to adjust its price $\pi_t = D_t^{-1}(\text{Supply}_t)$.

We assume that the mathematical expression of the demand function is not know by the operator. Hence, the operator needs to estimate it. At time t the operator has observed the previous price and demand realizations, that is, $D_1, \ldots, D_{t-1}$ and $\pi_{o,1}, \ldots, \pi_{o,t-1}$ and assumes a linear demand model $D_t = \alpha_{0,t} + \alpha_{1,t}\pi_{o,t} + \alpha_{3,t}$ where $\alpha_{o,3}$ is a random variable with zero mean and finite second moment. We propose an approximation for D_t by mean square approach i.e., the vector $(\alpha_{0,t}, \alpha_{1,t})_{t\geq 2}$ of the demand parameters through the solution of the least square problem given by $t \geq 3$,

$$(\alpha_{0,t}, \alpha_{1,t}) \in \arg \max_{(\beta_0,\beta_1)\in\mathbb{R}^2} \sum_{t'=1}^{t-1} \left(D_{t'} - \beta_0 - \beta_1 \pi_{o,t'}\right)^2,$$

Let $\alpha_t = (\alpha_{0,t}, \alpha_{1,t})$ and z_t the transposition of the vector $(1, \pi_{o,t})$ i.e., $z_t = (1, \pi_{o,t})'$. Then, a direct computation gives the following recursive equation for the demand estimation:

$$\begin{aligned} \alpha_{t+1} &= \alpha_t \\ &+ \begin{pmatrix} t & \sum_{t'=1}^{t} \pi_{o,t'} \\ \sum_{t'=1}^{t} \pi_{o,t'} & \sum_{t'=1}^{t} \pi_{o,t'}^2 \end{pmatrix}^{-1} z_t(D_t - z_t'\alpha_t) \end{aligned} \tag{4.9}$$

Note that if the matrix in (4.9) is non-invertible, the only solution is $\pi_{o,t} = cste, \; \forall o, \forall t$.

To summarize, at the operators level the problem writes,

$$\begin{aligned} \alpha_{t+1} &= \alpha_t + \\ \begin{pmatrix} t & \sum_{t'=1}^{t} \pi_{o,t'} \\ \sum_{t'=1}^{t} \pi_{o,t'} & \sum_{t'=1}^{t} \pi_{o,t'}^2 \end{pmatrix}^{-1} & z_t(D_t - z_t'\alpha_t), \\ D_t &= \alpha_{0,t} + \alpha_{1,t}\pi_{o,t} + \alpha_{3,t}, \\ \pi_{o,t+1} &= \pi_{o,t} + \hat{\lambda}_{o,t}\hat{d}_{o,t} \\ \hat{d}_{o,t+1} &= \hat{d}_{o,t} + \hat{\nu}_{o,t}\left(\frac{R_{o,t}}{\epsilon_n \xi_n} - \hat{d}_{o,t}\right) \end{aligned}$$

Remark 12. *Once the operators know their estimated spectrum demands and private valuation of the spectrum resource, they can formulate the bids and participate in the DSA auction carried out in the upstream market.*

4.9 Spectrum Resource Trading

We now model the interaction between operators and the spectrum broker in the current market. As mentioned earlier, the model is based on the uniform auction format.

4.9.1 Auction Model

We choose the uniform pricing auction to model the interaction at this stage, the motivation for choosing the mentioned auction format is the common use of this auctioning format in financial and other markets, which is evident by a large economic literature devoted to its study [1]. It is also argued that to a large extent, the FCC spectrum auctions can be viewed as a uniform-price auction (138). In a uniform-price auction, small bidders can simply bid their valuations and be assured of paying only the market-clearing price (139). The fact highlighted in (140) that in uniform price auctions the downstream playing field is level, in the sense that each licensee begins with the same foundational asset at the same price is also one of the motivating force to user the uniform price auctioning for spectrum trade. More on auction clearing algorithms can be found in (141).

We summarize the notations used in the auction model and their description in Table 1.1. In our formulation, the spectrum broker (virtualized LTE framework) is analogous to *auctioneer*, network operators are analogous to *bidders*, and the resource to be auctioned is analogous to *auctioned-item*. We assume that the *auctioned-items* are homogeneous and *perfectly divisible*. This assumption is strengthened by the fact that current trend of introducing flexibility in frequencies licensing i.e., providing operators with the technology neutral spectrum allocation. Let the distribution of auctioned item size has support in the range $[D_{min}, D_{max}]$, which defines the resource limits, where D_{min} is a single PRB size and D_{max} is the total capacity of the spectrum resource, hereafter we use $\hat{C}$ to represent the total resource capacity of the spectrum provider. Let there are $\tilde{\mathcal{N}}$ symmetric risk-neutral bidders (operators) who compete by simultaneously submitting their non-increasing demand functions $D_{o,k}$. These bidders have independent private valuation function of the auctioned item, which is driven by the bidders' demand and the service types. Although the resource is homogeneous, the bidders have different valuations for different amount of the resource. Such valuation is strictly influenced and is the consequence of the service types for which the resource is required. We assume that the market comprises of demands of two service types namely *Guaranteed service* and *Non-guaranteed*, intuitively the former has more strict resource requirements when compared with the later. Let the π_o be the bidder private valuation of the auctioned item. Influenced by the comment given in the preceding sentence, the bidder valuation varies for demands of different service types, this is captured by the index k, thus the bidder valuation now can be represented

[1] Ofcom, Award of available spectrum: 1781.7-1785 MHz paired with 1876.7-1880 MHz: A Consultation, 16 September 2005.

by $\pi_{o,k}$ such that $\pi_{o,k} \neq \pi_{o,\tilde{k}} \forall k \neq \tilde{k}$.[1] To illustrate this one has to consider the service demand patterns of the operators or putting it the other way operators spectrum valuation is driven by the operators' target market segment e.g., an operator targeting the fair users values the amount of spectrum demands for fair users more than the amount of spectrum for other user (service) types, the similar argument holds for vice versa. Thus the strategy for bidder $o \in \mathcal{N}$ is non-increasing function $D_o : [0, \infty) \rightarrow [0, D_{max}]$, and the his private valuation $\pi_{o,k}$, which is the evaluated spectrum price by the operator, the details of computing such valuation is given later in this section. Thus the operator bid is given by $\{D_{o,k}, \pi_{o,k}\}$. It should be noted that the valuation is computed as price per unit of the spectrum. We assume that the market behavior is represented by Equation 4.10, and we term this market as *spectrum trade market* hereafter. As can be seen that the demand curve is linear that expresses the demands as a linear function of the unit price. The choice of this market behavior is influence by its simplicity and wide presence in the literature.

$$\pi(D) := -\hat{\zeta} D + \gamma, \tag{4.10}$$

where $\hat{\zeta}$ and γ are positives, the negative gradient represents the sensitivity of market towards the price, and γ represents the bound on price. We know that the gradient introduces the elasticity in the curve. However, the proposed problem formulation dictates an inelastic spectrum demand behavior i.e., irrespective of how price may change the demand remains the same. This is represented by a perpendicular to the quantity axis in Fig 4.4. Given such inelastic scenario, what about the operators' valuation computation? So far the valuation is the price value at the intersection of the demand perpendicular and normal negatively sloped (going down from left to right) linear demand curve. However, this does not capture the operator preference for different services. To address this issue, we introduce the operator valuation function. Thus now the operator valuation corresponds to the intersection of operator valuation function slope and the demand perpendicular. As depicted in Fig 4.4, we map the operator demands over the spectrum trade market. The operator's the *valuation function* in this configuration is given by the Equation 4.11.

$$\pi_{o,k}(D) = \frac{D_{o,k}}{\pi_{o,k}} \tag{4.11}$$

where $\pi_{o,k}$ tunes the operators' valuation for the given demand and the service type such that; if the service type is of higher importance to the operator $\pi_{o,k}$ takes comparatively lower value

[1] Which may be (or may not be) the similar amount that users pay to the operator against the operator extended services.

than that of lower importance service. $\pi_{o,k}$ further can be translated as the function of number of operators in the spectrum competition and demands of service type i.e., real time service has higher value than that of background or non-real-time values i.e., $\pi(k, \tilde{\mathcal{N}} - 1)$. Although one may come up with any suitable $\pi(.)$ function, in this configuration, we simply represent it by a real-value exposed to simple constraint of $\pi_{k,o} \neq \pi_{\tilde{k},o} \forall k \neq \tilde{k}$ and $\pi_{o,k} \neq \pi_{\tilde{o},k} \forall o \neq \tilde{o}$. Furthermore, it should be noted from the Fig 4.4 that the price given by the intersection of the demand perpendicular and the negative slope of market curve is the upper bound on the prices set by the regulatory body.

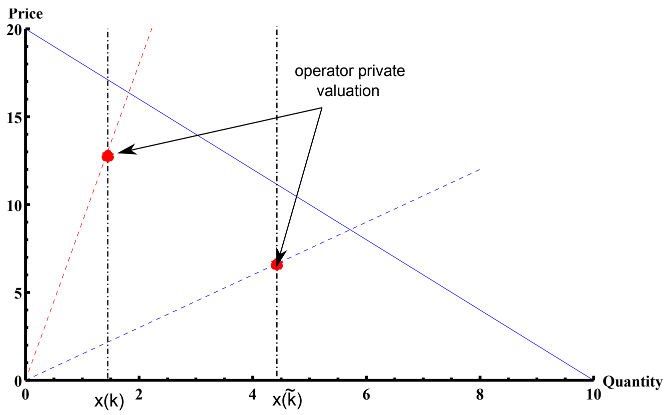


Figure 4.4: Figure representing the valuation of operators for different services - As can be seen that operators valuation for different services are the functions for demands and defined by the linear curves with different gradients, where the gradients may be translated as the private valuation of the operators for service type k. The intersection of operators' valuation curves and demands of service type k define the private valuation value for a particular demand value.

4.9.1.1 Observation

As explained earlier that this market is influenced by the downstream market i.e., user-operator market. In order to compute the *spectrum demand* estimates at the operator level, we carryout extensive simulation runs in different configurations using *Exponential Moving Average (EMA)* based on 20 seconds time intervals.

Definition 8. *The* operator valuation $\pi_{o,k}$ *is directly translated in to price quoted in the operators' bids, we term this as quoting the* "true valuation". *Intuitively, we denoted the false valuation by* $\tilde{\pi}_{o,k}$ *such that* $\pi_{k,o} \neq \tilde{\pi}_{o,k}$.

Let f be the mapping function that maps the downstream demands Y over the upstream demand function D, such that $f(Y) \mapsto D$. For simplicity we assume that the mapping is *bijective*. Given the upstream demand function an operator computes its valuation of resource using Equation 4.11. Realizing the upstream demand and by definition 8 the operator formulates its bid for the resource, which is given by $bi_o(D, \pi)$.

4.9.1.2 Allocation Rule

The allocation rule is implemented by the spectrum broker (LTE virtualization framework in this case), the consequence of implementing the allocation algorithm is the amount of spectrum allocated to the bidder. Let $\overline{bi}$ represents the highest bid, and p represents the stop out price then the allocation rule is given by:

$$\hat{a}_o(D_o, bi_o) := \begin{cases} D_o & \text{if} \quad bi_o = \overline{bi} \wedge D_o \leq \hat{C} \wedge bi_{o,k} > p \\ min\{D_o, \hat{C} - \sum\limits_{\tilde{bi}_{-o} \in B, \tilde{bi}_{-o} \setminus \{bi_o\}} D_{\tilde{bi}_{-o}}\} & \text{otherwise} \end{cases} \tag{4.12}$$

As can be seen from Equation 4.12 the operator which is declared as the highest bidder gets the resources equivalent to its demands. In case the operator does not occupy the highest bidder position and resides in the winner list then it is allocated the residual resources not necessarily equivalent to its demands. The operator gets the residual demand when the infrastructure resource capacity is less than the operator demands (lower part of Equation 4.12). The resource allocated to each operator is independent of the auctioning format, however the payments do depend on the auction format.

4.9.1.3 Operator Utility Function for Considered Configuration

As we know that operators have different valuation of different amounts (i.e., spectrum for k and $\tilde{k}$ type services) of spectrum. However, the allocation rule dictates that operators are allocated according to their aggregated demand request. Thus the operator profit function involves both spectrum amounts of different operator valuation values. We define the operator utility function for resource allocation a_o to operator $o \in \tilde{\mathcal{N}}$ and the stop-out price be p as:

$$u_o(p) := (\pi_{o,k} - p)D_{o,k} + (\pi_{o,\tilde{k}} - p)D_{o,\tilde{k}} \tag{4.13}$$

As can be seen that operator utility increases in its valuation and demands and decreases in stop-out price.

4.9.1.4 Auctioneer Utility Function

The profit function or utility function of auctioneer (In this work, we realize it through LTE virtualization framework) is the function of bidder demands and stop-out price and is given by:

$$u(\sum_{o \in \tilde{\mathcal{N}}} D_o, p) := \sum_{\tilde{b}i \in B} a_{\tilde{b}i} \times (p - \frac{\sqrt{D}}{\overline{\lambda}}) \tag{4.14}$$

where $\frac{\sqrt{D}}{\overline{\lambda}}$ represents the incurring cost of auctioneer, $\overline{\lambda}$ is the controller that enables the auctioneer to scale the cost that follows the operator specific deployment pattern (i.e., co-location, site rentals, tower rental, etc.), the detail modeling of cost function (modeling operational and maintenance, deployment costs, etc.) is out of the scope of this chapter. However, the choice of square-root function to capture the spectrum broker cost function is influenced by the continuous nature of the function for all non-negative numbers and differentiable for all positive numbers, the function also capture the realistic nature of the spectrum broker cost i.e., the spectrum broker initially incur more cost on improving service and such cost decreases with increase in demands. Spectrum broker maximizes its utility i.e., $max_p u_j(\sum_{o \in \tilde{\mathcal{N}}} D_{o,k}, p)$, which increases in *p* and allocated resources and constrained by the operators' capacities. Thus the problem that the auctioneer solves is to decide the auction clearing or stop-out price and resource allocation (for allocation rule see Equation 4.12) i.e.,

$$p = sup \left\{ p | \sum_{o \in \tilde{\mathcal{N}}} D_{o,k} \geq \hat{C} \right\} \tag{4.15}$$

We also present the algorithm that is implemented by the auctioneer to take the decision over resource allocation and stop-out price as follows:

4.9.2 Equilibrium analysis

We characterize the Nash equilibria in the mentioned model in weakly dominant strategies.

Lemma 1. *In an homogeneous item uniform price auctions, the operators with multiple bids have a unique dominant strategy for each bid in different instances i.e.,*

$$b_{o,t_1} := \pi_{o,t_1,k} \tag{4.16}$$

and

$$b_{o,t_2} := min\{\tilde{R}, \pi_{o,t_2,\tilde{k}}\}$$

Proof. We prove this by contradiction. Lets assume that operators are better off when they deviate from the mentioned bidding strategy. As can be seen from Equation 4.16, that bids are strictly increasing in value of π. Let $\pi_{o,t_1,k} > bi_{o,t_1,k}$ and $\pi_{o,t_2,k} > bi_{o,t_2,\tilde{k}}$, let there exists k bidders in the market, who value resource more than operator o, $\{k|k \in \mathcal{K}, \pi_{k,t_1} = bi_{k,t_1} > bi_{o,t_1,k} \&\& \pi_{\tilde{k},t_2} = bi_{\tilde{k},t_2} > bi_{o,t_2,\tilde{k}}\}$. This is the set of potential competitors and price setters in case of overloaded scenarios. It is assumed that capacity information is private information. Let us discuss the following cases: i) when $\hat{C} > D$, $\tilde{R} = 0$, then $bi_{o,k,t_1} < \pi_{o,k,t_1}$ and $bi_{o,\tilde{k},t_2} = 0$. In this case the allocation would be $\hat{a}_o(D) = D$ on the stop-out price = 0 the operator is better off. ii) when $\hat{C} < D$ and $\tilde{R}$ =non-negative value, we assume that R is public knowledge, keeping the bidding strategy very similar to the previous case. Then $\hat{a}_o(D) < D$ the operators are worse off, which contradicts the assumption. Thus owing to the property of sealed bid incentive compatible auctioning format, the operators will always have non-negative utility and operators are motivated to follow the bidding strategies in Equation 4.16. ☐

Algorithm 2: Calculate p and $\hat{a}_o$

Set t = 0 // Bids submissions start
Ensure: $bi_o \geq \tilde{R}$ // Ensure that bids are equal or above the *Reserve price* ($\tilde{R}$)
while $t \neq t_{max}$ **do**
  B $\leftarrow bi_o \forall o \in \tilde{\mathcal{N}}$ // Update the bid vector B for every income bid bi_o
end while
Determine the set of winning bids $LIST\overline{B} \leftarrow bi_o$ // The set of highest bids of B that do not violate the capacity constraint $\sum_{o \in \tilde{\mathcal{N}}} \hat{a}_o \leq \hat{C}$
SORT $LIST\overline{B}$ in ascending order.
p$\leftarrow LIST\overline{B}.bi_o(\pi)$ // select the price of lowest winning bidder as stop-out price.
while $\hat{C} \neq 0$ $\&\& LIST\overline{B} \neq$ empty **do**
Ensure: $bi_o \in \overline{B}$
  if $\hat{C} > bi_o(D)$ **then**
    $\overline{B}.B_o(\hat{a}) = D_o$
  else
    $\overline{B}.B_o(\hat{a}) = C_r$ // C_r is the residual capacity
  end if
end while

4.9.2.1 Sequence of Actions

1. Each bidder observes the demands (based on EMA, mentioned earlier).

2. Infrastructure provider announces the start of auction time t_{init} and duration of bid submission i.e., $t_{init} - t_{max}$.

3. Bidders submit their demands to the auctioneer at each per-unit price, which is the valuation of the bidder and attained from the Equation 4.11.

4. After the elapse of the submission time, the infrastructure provider observes the aggregated demand and sets the stop out price, which is equal or greater than the incurring cost over the unit resource. The auctioneer also decides each bidder's allocation.

5. The allocation is executed through the hypervisor

6. The process iterates over $1 - 4$, after the inter-auction time expires.

4.9.2.2 Multi period auctions configuration - a brief discussion

In this section, we form basis for the future milestones in this direction. We consider the environment with multi-period auctions over the infrastructure resource, it is assumed that the resource capacity owned by the infrastructure provider is a public knowledge. The configuration dictates that the total resources can be auctioned in multiple auction rounds, owing to the demand of service types, we restrict the framework to two-period auctions. In such settings the auctioneer needs to decide the amount of resource $b_g \forall g \in \{1, 2\}$ in both periods. This discern two sub-environments namely; i) Blind environment and ii) Vigilant environment. The earlier sub-environment dictates that auctioneer makes the number of auction period a public knowledge, whereas the latter is the converse. Investigating the future wireless dynamic market behavior in the mentioned configurations will be interesting research questions.

Considering the *sealed-bid uniform price* auction, where truth telling is *weakly dominant* strategy of the bidder (operators in this case), operators are motivated to bid their true valuation. However, in this configuration one thing to be considered is that the mentioned statement holds in the *last-period* only, and not in the earlier auction periods. This is illustrated by the fact that losing in the earlier periods still provide bidders to win in the last period. This argument raises interesting issues in the context of our resource sharing problem, where operators have different valuation over different amounts of resource demands. The operators' payoff within this configuration, when considering $\tilde{R} = 0$ is as follows:

$$u_o(k, x, \pi) := \begin{cases} \pi_{o,k} - p \qquad if \quad b_{o,k} > \overline{b}_{\hat{o},t_1 \forall o \in \tilde{\mathbb{N}}, o \neq \hat{o}} \\ \tilde{\gamma} Pr[max(\pi_{o,k} - \overline{b}_{o,t_2}, 0)] \qquad otherwise \end{cases} \tag{4.17}$$

where $\tilde{\gamma}$ is the discount factor and shows the risk taking behavior of the operators, a smaller discount factor $\tilde{\gamma}$ means that future rewards have less value compared to the current reward. Therefore a smaller discount factor represents a more risk averse operator. $\tilde{\gamma}$ also has physical interpretation in terms of the time spent between decisions. It in fact weighs the rewards in sequential decision problems. Within this environment since we assume that the number of auctions is a public knowledge, for this the dominant strategy of the bidder is given by:

$$b_{o,k,t_1} := \pi_{o,k} - \tilde{\gamma} Pr[\pi_{o,k,t_2}] \tag{4.18}$$

where $\pi_{i,k,t_2} = \pi_{o,k} - p_{t_2}$. Whereas the bidder optimal second price strategy if it does not win in the first period is $b_{o,k,t_2} = \pi_{o,k}$ An operator in the first auction would never bid anything above $\pi_{o,k} - \tilde{\gamma} Pr[\pi_{o,k,t_2}]$, because there is always positive probability that in this case the last winning bid is between the bid price and the $\pi_{o,k} - \tilde{\gamma} Pr[\pi_{o,k,t_2}]$. Which makes his expected payoff less than π_{o,k,t_2}. It can be observed that both the equilibrium bidding function increase in the $\pi_{o,k}$, it is clear that auctioneer allocates the goods with the highest valuations. However the auction may be inefficient in terms of a cost of delay, if the auctioneer chooses a two period auction when $\tilde{\gamma} < 1$. We will take care of these highlighted issues on granule levels in the future work and in parallel we expect to investigate in equilibrium strategies of all the stake holders within our technical framework.

4.10 Horizontal and Downstream Market (Markets 3 $\&$ 4)

Having acquired the spectrum both MVNO and MNP need to sell the spectrum resources to the users in downstream market, where users are free to make short-term contractual agreements (we assume that user-centric vision is realized), this reveals another competition between MNP and MVNO to win portions of common user pool. However, users on the other hand select the network provider(s) depending on utility obtained from the service related offers from the MNP and MVNO. We know that MNP and MVNO act in their self-interest i.e., increasing their utility functions. Thus they play strategies that increase their utilities, as explained earlier that the operators' strategies include the offer vectors, composed of QoS indices values and the service prices. Operators' formulation of offers are driven by the potential of operators (available resource and QoS improvement techniques, etc.) and the service price. Intuitively such offer formulation is dictated by the amount of spectrum acquired and the cost incurred on acquiring the spectrum in Market-2. Similar to non-cooperative incomplete information game among the users, the operators also do not have any information about other provider's strategies such that the price assigned for the service offered MOS values. In this market, we model the interaction between operators and users. We focus on the learning aspects of the proposed utilities and study the interactive trial and error learning for finding the equilibrium. Extending the concept of service priorities i.e., *Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit Rate (Non-GBR)* in LTE, we assume that there are three different types of users (on the similar lines as detailed in Chapter 2 and (142)) namely; i) Excellent, ii) Good, and iii) Fair. These users are characterized by their preference profiles e.g., an excellent user prefers the service quality, whereas a fair user is interested in service costs. We further assume that users broadcast the application requests in an abstract area a for three different types of applications namely; i) Voice over IP, ii) FTP, and iii) Video streaming. The modeling in this market is composed as following:

- Operator level: Each operator uses a network pricing scheme and allocates the resource to the users under the associated quality of service constraints (which is translated in to users QoE). Operators with lowest cost but with good QoS will be more and more congested. This will lead to saturation and bad QoS. When, increasing the prices, the users will switch to another class or operator in order to get better utility. This means that strategy of the operators are interdependent (the pricing of operator influence the others via the network repartition of users for each user type and service class).

- User level: At this level, each user seeks to maximize her utility with as low cost as possible.

- Interdependency between the levels: The prices fixed by the operators influence the user decisions: network selection based the set of operators that are the QoS requirement with lowest costs. In parallel, the decision of the users leads to a subnetwork for each operator. When maximizing her revenue, the operator needs to re-adapt its price in function of the user choice and the other operators. This leads to a interdependent multi-level system.

4.10.1 Network Operator Resource Allocation Problem

Each operator seeks to optimize its total revenue $R_o := \sum_{k,c} \pi(o,k,c) n^c_{o,k}$ subject to the QoS constraints. For the accepted users, a bandwidth allocation between the users is established. Then, each operator o designs the function π for each type k and each service class c.

4.10.2 User-Centric Network Selection Problem

At user level, the user problem is to select the suitable network operator. In this connection we need to model the user preferences and performance metrics. This will be captured by the utility function. Let $\mathcal{K}$ be the set of three different types of users, and U_i represents the utility of user i, $\forall i \in \mathcal{K}$. The expression of $U_i(.)$ is given as follows (similar to the one detailed in Chapter 2):

$$
\begin{aligned}
u_{i,k,c}(o,n) := \bar{u}_{i,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)\prod_{l\in L}(\nu_{il,o}(k,c,n))^{w_{il}} - \pi(o,k,c) \\
+ \sum_{l'\in L'} \omega_{l'} v_{il',o}(k,c,n,\psi),
\end{aligned}
\tag{4.19}
$$

The user utility function (Equation 4.19) has four components:

- The term $u_{i,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$ is the function of network state $n = (n^c_{o,k})_{o,k,c}$ and the offered bandwidth $b^c_{o,k}$ by the operator o. The collection n is the vector that represent the total number of users those request the service of specific class.
- $\prod_{l\in L}(\nu_{il,o}(k,c,n))^{w_{il}}$ is the weighted multiplicative approach for *dependent* associated QoE attributes.
- $\sum_{l'\in L'} \omega_{l'} v_{il',o}(k,c,n,\psi)$ is the weighted sum of different *independent* QoE attributes.
- $\pi(o,k,c)$ is the price of operator o to the user type k for service class c.

The first two multiplicative terms take into account both the congestion level of the operator and expected QoE, which is translated from the Operators QoS indices. The weight values w are dictated by the sensitivity of user type, service class to the attribute i. Here $k \in \Theta$, where Θ is the finite set of user types. Each operator o chooses its price vector π_o in a competitive way.

In order to formulate a utility function that respect the preference of the users and the performance metric of the network we use an experimental approach. *The expression of utility functions are given by experimental observations.*

Bandwidth dependent utility Availability of bandwidth / transmission data rate plays the key role in evaluating the user QoE, therefore most of the literature work focus on the impact of varying data rate/bandwidth over QoE. However the user satisfaction should be analyzed with respect to different technical and non-technical attributes, and QoE evaluation metric vary with respect to application used by the user. We capture the bandwidth dependent user satisfaction with the following utility function: $\tilde{t}_{i,k,c}(o,n) :=$

$$\begin{cases} 0 & \text{if } \frac{b^c_{o,k}}{n_{o,k}} \leq \underline{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}})\frac{1-e^{-\beta(b^c_{o,k}-\underline{b}^c_{o,k})}}{1-e^{-\beta(\overline{b}^c_{o,k}-\underline{b}^c_{o,k})}} & \text{if } \underline{b}^c_{o,k} \leq \frac{b^c_{o,k}}{n_{o,k}} \leq \overline{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}})\frac{1-e^{-\beta(b^c_{o,k}-\overline{b}^c_{o,k})}}{1-e^{-\beta(\tilde{b}^c_{o,k}-\overline{b}^c_{o,k})}} & \text{if } \overline{b}^c_{o,k} \leq \frac{b^c_{o,k}}{n_{o,k}} \leq \tilde{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}})\frac{1-e^{-\beta(b^c_{o,k}-\tilde{b}^c_{o,k})}}{1-e^{-\beta(\widehat{b}^c_{o,k}-\tilde{b}^c_{o,k})}} & \text{if } \tilde{b}^c_{o,k} \leq \frac{b^c_{o,k}}{n_{o,k}} \leq \widehat{b}^c_{o,k} \\ \mu_k(\frac{b^c_{o,k}}{n_{o,k}}) & \text{if } \frac{b^c_{o,k}}{n_{o,k}} \geq \widehat{b}^c_{o,k} \end{cases} \tag{4.20}$$

where $\mu_k(n_{0,k})$, represent the maximum utility of user types k and $n_{o,k} = \sum_c n^c_{o,k}$ is the number of users of type k for application quality of service class c from the operator o. In order to capture the congestion level, we choose the function α as strictly decreasing function in the number of users that request services at the same operator. The number $b^c_{o,k}$ represents the offered bandwidth to user type k for application quality of service class c, similarly $\underline{b}^c_{o,k}$, $\overline{b}^c_{o,k}$ etc represents the minimum and maximum required bandwidth by the application quality of service class c and user type k.

Now, we examine the outcome of the network selection in a competitive manner at the user level with the utility $\tilde{t}_i(.)$. At this level, each type of user seeks to maximize its utility $\tilde{t}_{i,k}(o,n)$. In this setting a well-studied solution concept is the called Cournot-Nash equilibrium. It is network configuration n^* such that for any i,k, the utility $\tilde{t}_{i,k,c}(o,n)$ is maximized by fixing the choice of the other users.

Next, we show that the user-centric game (the game at the user-level when the pricing functions chosen the operators are fixed) is in the class of congestion game (143). A finite game in strategic form is a potential game (144) if the incentive of all players to change their strategy can be expressed in one global function called the potential function.

Proposition 1. *The user-centric game is a finite potential game.*

Proof. Let π the pricing function chosen the operators. Since the utility $\tilde{t}_{i,k,c}$ contains only a congestion part via the total number of users $n_{o,k}$ for each range of bandwidth, one gets a standard congestion game which is known to be isomorphic to a *potential game*. The exact expression of the potential function can be obtained from (143, 144). □

Corollary 1. *The user-centric game has at least one pure Nash equilibrium.*

This result follows from the fact that the existence of pure Cournot-Nash equilibria holds in finite potential game (144). Here we apply it for each range of bandwidth.

4.10.2.1 Learning Aspects in Network Selection

The second issue that we address is the computation and the learning aspect of such equilibrium configurations. Different learning techniques have been developed for this specific class of games: finite improvement path, fictitious play, best response dynamics, stochastic fictitious play, etc. Most of these learning schemes require at least the information of the network states at the previous step which seems to be very strong assumption in our context.

Because the number of users in the hull network can be arbitrary large, observing and responding to the individual choice of all users on a frame of time units would be a formidable task for any individual user. Therefore, the standard fictitious play and the iterative best reply are not directly applicable. Note that in the finite improvement path procedure (FIP) only one user moves at a given time slot (simultaneous moves are not allowed). For this reason, the FIP is not adapted when the network does not follows a prescribed rule evolution.

One of the well-known learning scheme for simultaneous-move games is the trial and error learning. Interactive trial and error learning is a recent version of standard trial and error learning studied in (145) that takes into account the interactive and dynamic nature of the learning environment. In ordinary trial and error learning, users occasionally try out new operators and classes and accept them if and only if they lead to higher performance. In an interactive situation, however, "errors" can arise in two different ways:

- the active errors, those done by trying some new operator that turns out to be not better (in terms of QoS, price and performance) than what one was chosen, or
- the passive errors, those done by continuing to keep the old strategy that turns out to be worse than it was before (due to congestion, new traffic conditions etc) .

In (145), it is shown that the interactive trial and error learning, implements Nash equilibrium behavior in any game with generic utilities and which has at least one pure Nash equilibrium. The interactive trial and error learning is a fully distributed learning rule such that, when used by all users in a game, period-by-period play comes close to pure Nash equilibrium play a high proportion of the time, provided that the game has such an equilibrium and the payoffs satisfy an interdependency condition. Since our finite utility given by the $\tilde{t}_i(.)$ has at least one equilibrium, the learning procedure implements one of the equilibrium with proportion of the time.

We assume that each user makes selection and service request decisions in random frames to optimize its own objectives in response to their own observations and local clocks and is able to measure a numerical value of its benefit and pay a cost for the service that he/she consumed. He is able to evaluate $\tilde{t}_{i,k,o}$ if the tried operator is o. Based on this measurement the user update his/her strategy when he/she will be active: keep the strategy with probability $(1-\epsilon)$ if the performance is greater or try another strategy with probability ϵ. All this is done for a well-chosen $\epsilon \in (0, 1)$.

Proposition 2. *The interactive trial and error learning algorithm implements a pure Nash equilibrium of the user-centric game with high proportion of times.*

Proof. We verify that the conditions in (145) are satisfied. First, the user-centric game is a finite game for any fixed pricing function π. Second, the game is not degenerated because the utility functions are strongly interdependent via the network state. Third, we know that the game has at least one equilibrium from the corollary 1. Combining together all the conditions in (145) are satisfied. The result follows. $\square$

Learning in Dynamic Environment Since the network is dynamic the associated game model should capture the variabilities, network traffic and the randomness in the environment. To this end, we extend the learning framework to dynamic game. For more details, we refer to (40) in which the number of active users may be random, new users come in, and exit, etc. Without knowledge of the network state, without knowledge of the distribution of users, each active user tries to find out his/her utility function and associated payoff in the long-term (40).

Price of Anarchy and Sub-optimality Note that, even if this learning algorithm implements Nash equilibria of the game, the convergence time to be close to an equilibrium can be arbitrary high. Moreover, it is known that the equilibrium can be inefficient in term social welfare. The performance gap between the total equilibria utilities and global optimum is sometimes referred to *price of anarchy*.

In order to reduce this gap, the operators can design new game via their pricing functions. Under appropriate pricing functions π, one can design a game such that the equilibrium configuration of the new game (the utility is the difference between profit and cost) is near-optimal. This leads to the utility U_i (instead of $\tilde{t}_i$). Important components of U_i are the attributes dependent utilities v_{ij} and the cost functions π.

4.10.3 Risk-sensitive User-Centric Network Selection

Based on experimental utility functions, we study the behavior of users under risk-sensitive criterion. Mixed (or randomized) actions have been widely examined in game theory and its applications. When at least one of the users randomizes its action, the resulting payoff of the users become a random variable. The classical approach resulting from von Neumann & Morgenstern utility theory suggests using the mathematical expectation of the payoff function also called *expected payoff*. The expected payoff has natural interpretation in statistics and in learning theory based on the basic observation from the law of large numbers and ergodic theory.

If the game is played infinitely many times and the users always implement a fixed randomized action profile, then the average payoff really obtained by the users converge with probability one to the expected payoff.

However, not all behaviors can be captured by the expectation criterion referred also as *risk-neutral criterion*. To illustrate this, consider the following two scenarii:

A user is given the choice between two networks, one with a guaranteed payoff and the another without guarantee.

Scenario 1: In the guaranteed scenario, the user gets 10 surely.

Scenario 2: In the uncertain scenario, a coin is flipped to decide whether the user receives 20 or 0 Each user gets a 0 with probability 1 if he/she looses and he/she gets $+20$ with probability 1 if he/she wins. Each user wins or looses with probability $1/2$.

Using the classical approach with the expected payoff criterion, the scenario 1 and the scenario 2 leads to the *same outcome*. The expected payoff for both scenarios is 10, meaning that a user who was insensitive to risk would not care whether they took the guaranteed payoff or the gamble. However, users may have different risk attitudes. It is clear that in scenario 2, the user faces a big risk which can be reflected by the variance (or higher moments) of the outcome. A risk-neutral user ignores the risk. However, there is always a risk whenever the action profiles are selected at random. A risk-averse user would accept a payoff of less than 10 (for example, 5), with no uncertainty, rather than taking the gamble and possibly receiving nothing. A risk-seeking user would accept the guaranteed payoff must be more than 10 (for example, 15) to induce him/her to take the guaranteed option, rather than taking the gamble and possibly winning 20.

The first step to take into consideration this phenomenon is to modify the expected payoff criterion to incorporate also variance, third moments, etc.

Let $var(U_i) = \mathbb{E}[(U_i)^2] - (\mathbb{E}[U_i])^2$ be the variance of the payoff where U_i is the payoff function of user i. Note that the function $\mathbb{E}[U_i] - var(U_i)$, is not necessarily well-adapted due to his non-existence properties. A criterion that takes into consideration all the moments of the random payoff could be

$$\tilde{r}_{i,\mu_i} = \frac{1}{\hat{\mu}_i} \log \left[\mathbb{E} e^{\mu_i U_i} \right],$$

where $\hat{\mu}_i \neq 0$ is the risk sensitivity index.

Using Jensen's inequality, for $\hat{\mu}_i < 0$, the certain equivalent payoff $\tilde{r}_{i,\hat{\mu}_i} \leq \mathbb{E}U_i$ and when $\hat{\mu}_i > 0$, the opposition inequality holds. In the first case ($\hat{\mu}_i < 0$) a user having negative risk factor $\hat{\mu}_i < 0$ and grading a random payoff according to the certain equivalent payoff $\tilde{r}_{i,\hat{\mu}_i}$ is referred to risk-averse and the second case ($\hat{\mu}_i > 0$) is referred to risk-seeking .

It is obvious that the certainly equivalent payoff $\tilde{r}_{i,\hat{\mu}_i}$ takes into consideration all the moment of the payoff U_i. By doing a Taylor expansion for $\hat{\mu}_i$ close to zero, one gets,

$$\tilde{r}_{i,\hat{\mu}_i} \underbrace{\approx}_{\hat{\mu}_i \sim 0} \mathbb{E}U_i + \frac{\hat{\mu}_i}{2} var(U_i) + o(\hat{\mu}_i).$$

A game with risk-sensitive users (one index $\hat{\mu}_i$ per user) is called *risk-sensitive game*. The equilibria of such games are *risk-sensitive equilibria*.

Proposition 3. *The finite risk-sensitive game has least one risk-sensitive equilibrium in mixed strategies.*

Proof. We check the basic properties for existence of fixed-point. Continuity is obtained by log-multilinearity. Concavity with respect to each variable follows for the concavity of the logarithmic function and strictly monotonicity and positivity of the exponential. Convexity of the domains are guaranteed by randomization over finite sets. Then, the existence of risk-equilibria in finite games is straightforward by using Kakutani's fixed point theorem. □

4.11 Realizing the Spectrum Broker Concept

In this section, we discuss the realization of spectrum broker that we proposed in Market-2. It should be noted that in this chapter, we propose the technical realization formulation for the spectrum broker only. This is due to the fact that we already discussed the realization framework for the operator-user telecommunication chain (based on user-centric concept) in

Chapter 3. We realize spectrum broker concept by making use of LTE virtualization concept and implement the Market-2. The motivation to use LTE virtualization for realizing the market comes from LTE's more appropriate nature.

4.11.1 LTE and the Virtualization Framework

In this section, we discuss the LTE virtualization framework that we implement extensively to realize the proposed dynamic spectrum allocation concept. We virtualize the LTE network infrastructure (i.e., eNodeB, routers, ethernet links, and aGW, etc.) so that multiple mobile network operators can create their own virtual network (depending on their requirements) on a common infrastructure. In the proposed virtualized network, we mainly foresee two different aspects;

1. Physical infrastructure virtualization: virtualizing the LTE nodes and links,

2. Air interface virtualization: being able to virtualize the LTE spectrum.

However, we in this chapter focus on the later aspect, since virtualizing the air interface of the LTE system is a completely new concept and also the earlier aspect is extensively investigated in the research literature.

4.11.2 Air Interface Virtualization

As we know that eNodeB is responsible for accessing the radio channel and scheduling the air interface resources between the users. Thus virtualizing the eNodeB in turn serves the purpose of the virtualizing the air interface. It can also be noted that virtualizing the eNodeB is similar to node virtualization. The physical resource of the node (e.g., CPU, memory, I/O devices, etc.) are shared between multiple virtual instances. In this connection various virtualiztion solutions are available e.g., OpenVZ (146), VMware (147), and XEN (148), etc. However, in this work, We use the well known PC virtualization solution XEN that inserts a layer called "Hypervisor" on top of the physical hardware to schedule the resources. Our LTE virtualization framework follows the similar format i.e., a hypervisor is added on top of the PHY layer of the eNodeB which is responsible for virtualizing the eNodeB node as well as the spectrum. The abstract view of the LTE virtualized framework is presented in Fig 4.5.

As can be seen in the architectural figure that the physical eNodeB virtualized into a number of virtual eNodeBs. This is achieved by the hypervisor that sits on top of the physical resources

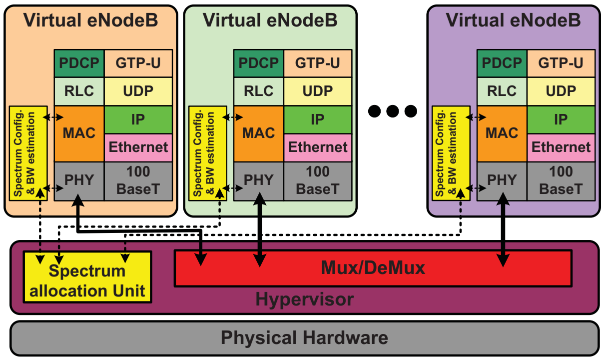


Figure 4.5: LTE eNodeB virtualization framework architecture - The figure represents different protocols and components which were implemented to realize the spectrum trade market.

of the eNodeB. In addition, the hypervisor is also responsible for scheduling the spectrum, i.e., scheduling the air interface resources (OFDMA sub-carriers) between the virtual eNodeBs running on top. In the framework architecture two new entities should be highlighted: the "*Spectrum configuration and Bandwidth estimation*", which are responsible for setting the spectrum the virtual eNodeB is supposed to operate in as well as estimating the required bandwidth of the operator. The "*Spectrum allocation unit*" which is responsible for scheduling the spectrum among the different virtual eNodeBs. LTE uses OFDMA in the downlink, which means that the frequency band is divided into a number of sub-bands that are called Physical Resource Blocks (PRBs). A PRB is the smallest unit the LTE MAC scheduler can assign to a user. The Hypervisor schedule the PRBs between the different virtual operators, this process could be done by different mechanisms. In this chapter, we use the auction based mechanism is used in the "*Spectrum allocation unit*" to auction the PRBs to the different virtual operators that bid for them.

Definition 9. *The reserved price ($\tilde{R}$) is the minimum price the auctioneer is willing to sell the resources with, and any bid with a price lower than the reserved one will be rejected.*

4.12 Simulation Model, Scenarios and Configurations

The LTE virtualization simulation model is developed using OPNET (149) based on the 3GPP specifications. As explained earlier, the focus of the model is on the air interface virtualization and spectrum sharing between multiple virtual operators (all sharing the same eNodeB). An example scenario of the simulation model can be seen in Fig 4.6.

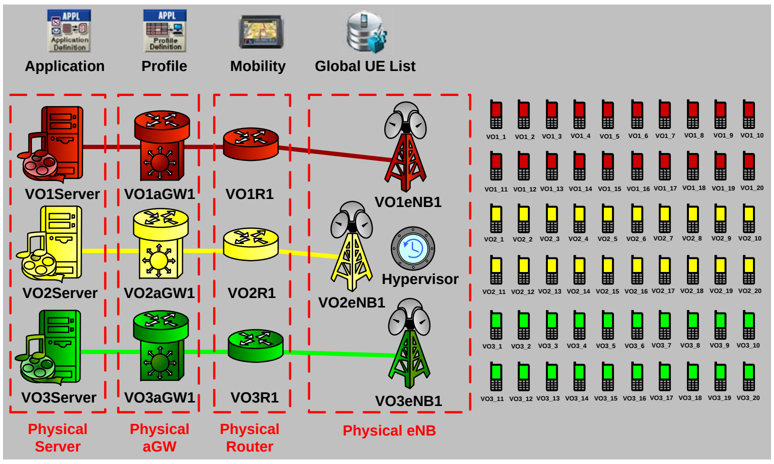


Figure 4.6: OPNET simulation model for LTE virtualization - Figure represents the screen shot of the developed LTE virtualization framework where an hypervisor (spectrum broker) trade the spectrum rights among three different virtual operators.

In order to study the gain of realized virtualization based spectrum broker concept, we carried out the measurements for two different scenario configurations namely: *no-reservation price configuration* and *with reservation price configuration*. In the following, we detail on the measurements in the mentioned configurations.

4.12.1 No Reservation Price Configuration

In this settings, we assume that the spectrum broker does not declare the *reservation price* for the spectrum unit. Given *zero reservation price* as the public knowledge, the operators may adopt the strategy of quoting the false valuation of the resource in their bids, thus quoting the false valuation will be dominant strategy (specifically in the formulated problem, where for homogeneous items, operators have different valuations). Our objective of analysis in this settings is twofold, on one hand implementing the scenario, we ensure the proper functioning of implemented LTE virtualization framework. On the other hand, we aim at studying the profit gain of virtual operators by declaring false private valuation of the spectrum resources.

4.12.2 With Reservation Price Configuration

In this configuration, the spectrum broker sets different reservation prices for the spectrum resources. We assume that reservation price is the function of spectrum demands (as shown in Equation 4.21). In this configuration, we concentrate on investigating the impact of reservation price (declared by spectrum broker for the spectrum resources) over the profit of virtual operators and spectrum broker. We are also interested in studying the spectrum utilization patterns.

$$\tilde{R} = \tilde{\gamma} \cdot \sqrt[3]{\sum_i \sum_k x_{i,k}} \tag{4.21}$$

For more on simulation setup configuration refer to Table 4.2.

Parameter	Assumption
Number of virtual operators	4 virtual operators with circular cells of 375 meters radius
Total Number of PRBs (Spectrum)	75 PRBs i.e., about 15 MHz
Mobility model	Random Way Point (RWP) with vehicular speed (120 Kmph)
Number of active users per virtual operator	Virtual Operator-1 (VO_1): 16 GBR (video users) and 4 non-GBR (FTP users) Virtual Operator-2 (VO_2): 10 GBR (video users) and 10 non-GBR (FTP users) Virtual Operator-3 (VO_3): 4 GBR (video users) and 16 non-GBR (FTP users)
VO_1 price valuation	π_1=2 and π_2=(2, 4, 6, 8, 10 and 20)
VO_2 price valuation	π_1=2 and π_2=4
VO_3 price valuation	π_1=2 and π_2=2
Video traffic model	24 frames per second with frame size = 1562 Bytes Video call duration = Exponential with 60 seconds mean Inter video call time = Poison with 30 seconds mean
FTP traffic model	FTP file size = 8M bytes Inter request time = uniform between 50 and 75 seconds
Auctioning parameters	Auction done every 20 seconds with $\tilde{\gamma}$ = 0.25
Simulation runtime	1000 seconds

Table 4.2: Simulation configurations - The table contains simulation parameter values for both the considered scenario configurations

4.13 Results and Analysis

A number of simulations were run to investigate behavior of virtual operators and spectrum broker in the two mentioned configurations. Fig 4.7 and Fig 4.8 show the profit gain of virtual operator 1 in both *no reservation price* and *with reservation price* configurations. As can be seen that operator's profit gain increases in the private valuation in the scenarios with $\tilde{R} = 0$,

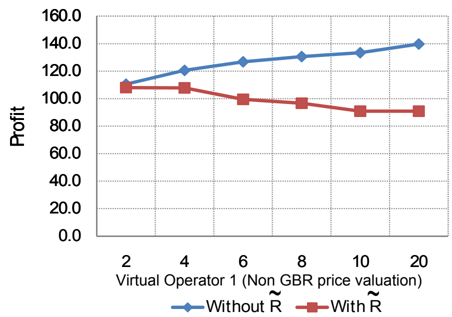


Figure 4.7: Average virtual operator 1 profit per auction - The figure presents the behavior of operator's profit gain for both *no reservation price* and *with reservation price* configurations. As can be seen from the curves that in the earlier configuration, the dominant strategy of operator will be to quote the false valuation, as its profit increases in false valuation bidding.

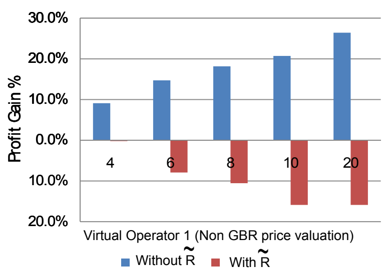


Figure 4.8: Relative virtual operator 1 profit gain compared to π = 2 - The figure presents the relative profit gain of operator 1.

whereas a converse behavior is observed for configuration with $\tilde{R} > 0$. It should be noted that the profit is scaled between the range $0 - 160$, such scaling is done to observe the behavior of profit gain on an understandable format. We believe that for any scaling function, the operator's profit gain will present similar behavior.

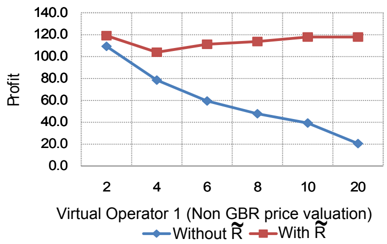


Figure 4.9: Average spectrum broker profit per auction - Figure shows the profit gain of the spectrum broker in both the configurations. The profit gain of spectrum broker is analyzed for different valuation values. It should be noted that the profit unit is scaled and for any profit unit the profit behavior will remain similar to the curves presented in the figure.

On the similar lines, we analyze the profit of spectrum broker in both the configurations. The results are presented in Fig 4.9 & 4.10. Intuitively the spectrum broker gains in declaring the reserve price. However, the decision of *what reserve price is to be declared* is a crucial issue. As stated earlier, in this work we model the decision over reservation price as a function of the aggregated spectrum demands.

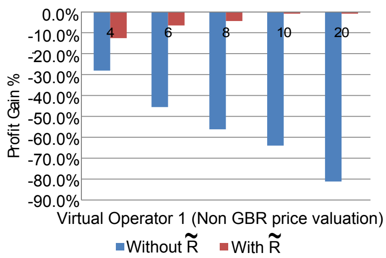


Figure 4.10: Average spectrum broker profit per auction - Figure shows the profit gain of the spectrum broker in both the configurations. The profit gain of spectrum broker is analyzed for different valuation values. It should be noted that the profit unit is scaled and for any profit unit the profit behavior will remain similar to the curves presented in the figure.

As the simulation environment comprises of multiple virtual operators (i.e., four virtual operators), we investigate the profit gains of other three operators on the similar lines as that of operator 1. Fig 4.11 & 4.12 show the average profit gains and relative profit gains of operator 2 respectively. Similarly Fig 4.13 & 4.14 depict the average profit gains and relative profit gains of operator 3 respectively. One can easily observe that for both the configurations, the

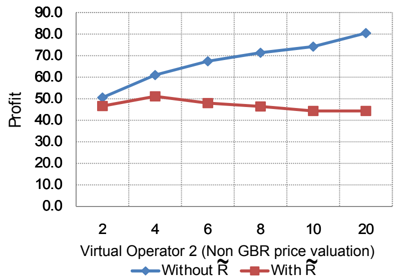


Figure 4.11: Average virtual operator 2 profit per auction - Figure depicts the profit gain of operator 2 for different operator valuations of the spectrum resource.

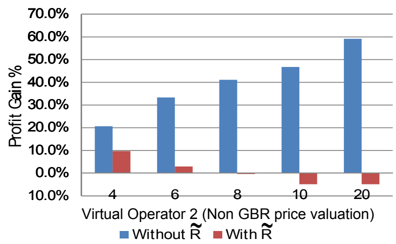


Figure 4.12: Virtual operator 2 profit and relative profit gain - Figure represents the relative profit gain of operator 2.

behavior of all the operators in terms of profit gain remain the same. However, a shift of almost 50% in the profit gain of operator 2 for different values of π is due to the different private valuation of the spectrum resources by the operator 2. We also investigate the inefficiency

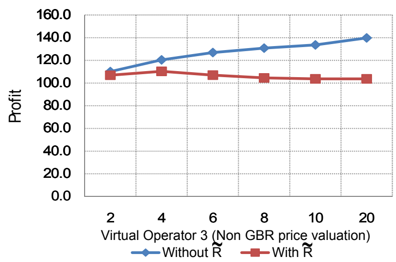


Figure 4.13: Average profit gain of virtual operator 3 per auction - Figure represents the operator's gain in terms of profit for different valuation values of the operators in both the simulation configurations.

introduced by the higher reservation prices in Fig 4.15 & 4.16, the inefficiency is basically

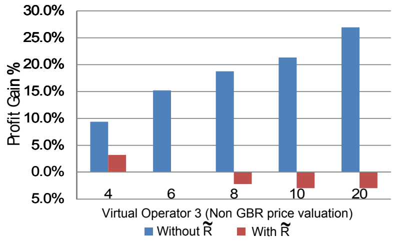


Figure 4.14: Relative virtual operator 3 profit gain compared to virtual operator π=2 - The figure represents relative gain of operator 3 against the profit gain of virtual operator 1 (i.e., against the operator 1's π=2).

denoted by the spectrum under utilization. We carried out simulations for different values of π to capture the operators' behavior for different valuations. One can observe in Fig 4.15 that for higher priority services (the services, which are highly valued by the operators e.g., π = 2). The introduction of *reservation prices* has least effect. However, the *reservation prices* consequence in greater *under utilization of spectrum resources* with decrease in the private valuation of the spectrum resources by the operators. This behavior is justified by the fact that the higher value of π advocates that operators are less damaged when they remain unsuccessful in winning that spectrum or putting it the other way, this behavior may be translated as the operators prefer losing the auction rather then paying more than the valuation (which can be translated in negative utility of operators). Similarly in Fig 4.16, we analyze

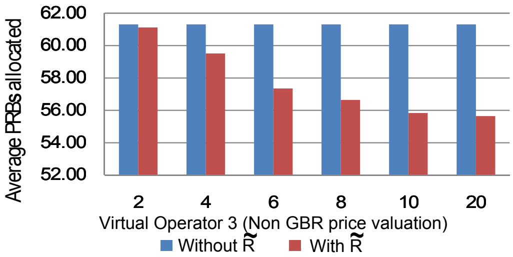


Figure 4.15: Spectrum broker's overall resource utilization - Figure representing the resource utilization comparison in *no reservation price* and *with reservation price* configurations. As can be seen that market efficiency (in terms of resource utilization) is compromised by introducing the reservation price.

the operators' resource allocation in both the configurations. Obviously operators allocated resources in both the configurations follow similar pattern for higher private valuation of the operators. However, the spectrum resource utilization decreases for the lower private valuation of the spectrum resources. From the analysis, we conclude that the proposed dynamic spectrum

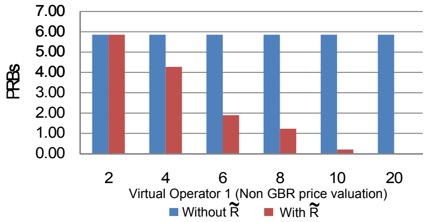


Figure 4.16: Operator's resource utilization pattern - Figure representing the resource operator's utilization pattern in *no reservation price* and *with reservation price* configurations. As can be seen that operator's allocation decreases with increasing reservation prices, which may be translated as the reservation prices tune the operator's demands for spectrum resources.

allocation approach and the proposed technical realization approach introduces efficiency in the spectrum allocation market both in terms of resource utilization and the profit of stake-holders.

4.14 Conclusion

In this chapter, we focused on investigating the strategies of different telecommunication players in a wider perspective. We model the interaction among these players and studied the equilibrium strategies using game theoretic approaches. We basically define the relationships of different stake-holders in the de-regulated telecommunication markets. The chapter focuses on discussing the dynamic spectrum trade realization aspects and dynamics of such market is evaluated by extensively implementing the LTE based virtualization simulation setup.

Part II

Operator Centric Category

In this category, we concentrate on investigating the efficiency in the network resource allocation by network operators. We model the resource management in a single operator, multi-operators scenarios, and study the efficiency of the proposed models in different settings. The motivation behind studying the network-centric resource allocation comes from the following facts:

- Current communication market is network-centric, where the objective of a network provider is driven by the efficiency in resource utilization, which can further be translated into operator's revenue. Thus a rational operator strives to maximize its revenue. It should be noted that most of the research literature in this direction can in general be grouped under the title of *throughput optimization problems* and such solutions do not specifically take into account the user satisfaction (QoE) for the extended services.

- One of the telecommunication business model dimensions is that operators may form a joint venture and such decisions may be time and space specific. Thus in such a case, the resource sharing approaches should be investigated for their efficiency.

- Having attained the results for network centric resource allocation, we will be in position to compare the performance of proposed network centric resource allocation and user centric network selection approaches in terms of radio resource utilization, call blocking, etc. However, for such performance comparisons, scenarios have to be made comparable.

This category basically comprises of the following three chapters:

- **Chapter 5** *Network Centric Resource Allocation - Single Operator Perspective* : This chapter focuses on the resource allocation within the single operator scenario, where the model for resource sharing based on cooperative game-theoretic approach is proposed. The performance of the proposed approach is analyzed in terms of resource utilization, call blocking rate, and compared against the earlier approaches in the research literature.

- **Chapter 6** *Network Centric Resource Allocation - Multiple Operator Perspective* : This chapter extends the proposed model of the single operator resource allocation approach to the multi-operator scenario. Interaction among different players (operators and network technologies) is modeled at two hierarchical levels. The resource utilization efficiency is analyzed for all the involved operators.

- **Chapter 7** *Performance Evaluation of Network Centric against User Centric Approach* : This chapter studies the operators' gain in user centric network selection and network centric resource allocation settings in terms of radio resource utilization and call blocking.

In Table 4.3, we present the notations used in this category and the description for these notations.

Table 4.3: Notations and their descriptions

Notation	Description	Notation	Description
N	set of network technologies	O_{th}	operation threshold region
ψ	load balancing factor	M	set of operator policies
$b_{k,c}(\pi)$	Predefined offered bandwidth	$\tilde{c}_w$	network w available capacity
c	application class	π_p	potential-based policy
k	user type	π_h	hard-coded policy
W^a	Uncongested network technology set in area a	$\overline{W}^a$	congested network tech. set
β	proportionate factor	$u_{w,k,c}$	network tech. utility function
$r_{k,c}$	requested bandwidth of user k for service class c	$x_{k,c}$	allocated bandwidth
a	abstract coverage area	S	feasible allocation set
d	disagreement point	π_{co}	congestion based policy
o_w	total capacity of network w	X^*	bargaining solution
l_w	current load on network w	λ	decision boolean
$\tilde{\mu}$	maximum utility	$B_{k,c}(\pi)$	aggregated operator bandwidth
pr	operator per unit charged price	ch	operator per unit cost
$\tilde{C}^a$	sum of available bandwidths of all networks in area a	ν_o	operator utility
$\mathcal{I}$	finite set of users	$\bar{\mu}$	mean value
$\mathcal{K}$	set of user types	α	maximum achievable utility
$r_{k,c,}$	user type k request of application type c	$\bar{C}_{w,p}$	incurred cost
$bi_{k,c,w,p}$	bid by operator p through technology w for		
	the application request c of user type k	$U_{w,p}$	operator utility
$\bar{\pi}_{k,c,w,p}$	per unit bandwidth payment to operator p for service class c		
$u_k(r^f_{k,c,p})$	user k utility obtained by offered bandwidth r^f	$\bar{\psi}_k$	user type k assigned weight
$\bar{\beta}$	decaying factor representing the user utility		
	sensitivity to considered evaluation parameter	Cr	Creditors
π	Operator policy	Pr	operator pricing scheme
$b^{w_1}_{max}$	offered bandwidth by w of op-1	$B^{\bar{a}}_{k,c,p}$	offered bandwidth vector
$R^a_{k,c,p}$	Request vector	$\bar{D}(c)$	vector of disagreement points
$\psi_{p,w}$	load balancing factor	μ	motivation factor

5

Network Centric Resource Allocation - Single Operator Perspective

The increasing number of radio access technologies and the availability of multi-radio devices boost the need for novel resource allocation schemes in cellular networks. This chapter uses a cooperative game theoretic approach for resource allocation at the network level, while utilizing simultaneous use of available radio interfaces at the device level. We model resource allocation management using the well known bankruptcy model and apply Kalai-Smorodinsky bargaining solution method to find a distribution rule, based on which we propose resource allocation and call admission control schemes. Performance analysis of our allocation and control schemes demonstrates significant improvements over previous approaches in terms of utilization of the available bandwidth and the number of call drops. We also study the performance of proposed approach for different operator policies.

5.1 Introduction and Related Work

We observe an increasingly heterogeneous landscape of wireless access technologies, including UMTS, LTE, WiFi, WiMAX, etc. These technologies are specialized for different environments and user contexts. The development as well as the business cycles of these technologies can assure us that they will be available simultaneously for the years to come. Consequently, there has been significant research activity on the integration and inter-interoperability of these fundamentally different access technologies, which exhibit different service characteristics in terms of bandwidth, coverage, pricing, and QoS support. The initial concern for network operators was increased connectivity by providing diversified methods of access for different types of end devices. However, the emergence of multi-interface terminals has shifted the simple connectivity issue to more rewarding resource allocation problems, whose solutions aimed at increasing the network efficiency and capacity as well as improving users' experience for ample amount of services such as video on demand, video conferencing, and a variety of other applications.

Common Radio Resource Management (CRRM) (150) is the concept that multiple such RAT can be combined in an operator network to diversify the service offer, as well as make use of trunking gains. The CRRM problem, which involves the allocation of call requests of different service types to the different Radio Access Networks (RANs), has been approached mostly from a single operator perspective, where different RATs)are deployed as radio access networks belonging to the same operator.

Within this framework, one can discern two approaches. On the one hand it was shown by Fruskär et al. (151) that the optimal policy to maximize the combined utilized bandwidth on the RANs is to associate individual RANs to a certain service type that they support better than the others, and then to mix traffic only when one RAN is full. We call this approach the service-based approach. On the other hand, the work of Tolli (152) concentrates on the trunking gain that is obtainable by balancing the load between different RANs. This approach relies on a periodic measurement of the load situations on the RANs and allocating the service requests to the RAN with the most capacity. We call this approach as capacity based approach.

Although extensive research has been carried out on improving vertical handovers and improving user QoE through service adaptation to suit the characteristics of network interface, most of these research confined to the use of a single network interface at any given time to meet the requirements of applications (see e.g., (153, 154, 155, 156)). More recently, the possibility to use multiple access technologies simultaneously and to split an application's resource requests among available RATs has been investigated. The "Ambient Networks" project (157) within the EU Framework Program 6 (FP6) introduced a *Generic Link Layer* (GLL), integrating different RATs at the link layer for efficient interworking (158). A byproduct of GLL is Multi-Radio Transmission Diversity (MRTD), which allows splitting of data flow among multiple RATs. In (159) Bazzi et al. also investigated the issue of using multiple RATs simultaneously at the terminal, concluding that parallel transmission over multiple RATs by a careful resource allocation scheme allows one to achieve a throughput as high as the sum of the throughput obtained by the use of each individual access technology.

As in many areas of the networking field, application of game theory concepts to CRRM problem has been considered using both cooperative ((2, 160)) and non-cooperative / competitive ((115),(116), (117)) game models to obtain efficient resource allocation schemes. Badia et al. provided a comparison between non-cooperative and cooperative models in resource allocation and demonstrated that collaborative strategies are able to improve the overall system performance (161). A *bankruptcy game* is used in (2) to model the problem, but within a limiting scenario regarding the composition of available access technologies.

In this chapter, we address the issue of multi-radio resource allocation in generic heterogeneous wireless networks using a cooperative game, where the network technologies cooperate with each other to attain the ultimate goal of user satisfaction. We use the Bankruptcy model and apply *Kalai-Smorodinsky Bargaining Solution (KSBS)* to find the distribution rule that best fits our objective of simultaneous resource allocation for channel requests. We also provide extensions of our approach to handle the mobility of users between coverage areas with different composition of access technologies.

5.2 Relevant Background

We start by reviewing several basic definitions and concepts that will be utilized in this work related to the bankruptcy problem and bargaining solution of cooperative games. We also provide a brief overview of different access technologies and their characteristics affecting our resource allocation problem.

5.2.1 Bankruptcy Problem

Bankruptcy is a distribution problem, which involves the allocation of a given amount of goods among a group of agents, when this amount is insufficient to satisfy the demands of all agents. The available quantity of the goods to be divided is usually called estate and the agents are called creditors. The question here is: *How to distribute estate amongst creditors?* A number of distribution rules have been proposed to deal with such problems. The solution to a bankruptcy problem can be interpreted as the application of an allocation rule that gives sensible distribution of estates as a function of agents' claims. Bankruptcy is a pair (E, Cr), where E represents the estate to be distributed among a set Cr of the claims of n creditors, such that

$$Cr = (cr_1, \dots, cr_n) \geq 0 \quad \text{and} \quad 0 \leq E \leq \sum_{i=1}^{n} cr_i. \tag{5.1}$$

An allocation x_i of the estate among creditors should satisfy

$$\sum_{i=1}^{n} x_i = E \quad \text{given that} \quad 0 \leq x_i \leq cr_i. \tag{5.2}$$

In our formulation creditors represent the access networks and estate represents the required bandwidth by applications.

5.2.2 Bargaining Solutions of Cooperative Games

Bargaining (162, 163) refers to the negotiation process (which is modeled using game theory tools) to resolve the conflict that occurs when there are more than one course of actions for all the players in a situation, where players involved in the games may try to resolve the conflict by committing themselves voluntarily to a course of action that is beneficial to all of them. Application of bargaining solution to bankruptcy problem is natural in that bankruptcy problems create the situation of conflict over distribution of estate and to resolve the conflict the creditors (players) negotiate to get to the point of agreement. Such negotiations are best framed using bargaining solutions.

5.2.3 Kalai-Smorodinsky Bargaining Solution

Given a pair (S, d) that defines the general bargaining problem, with S denoting the set of feasible utilities and $d \in S$ representing the disagreement point, the unique Kalai-Smorodinsky bargaining solution $X^* = F(S, d)$ fulfills the following axioms:

1. Individual Rationality: $X_i \geq d_i$ for all i
2. Feasibility: $X^* \in S$, the solution should be a member of the feasibility set.
3. Pareto Optimality: X^* should be Pareto optimal.

   A solution is Pareto optimal if it is not possible to find another solution that leads to a strictly superior advantage for all players simultaneously (164).
4. Translation Invariance: $\forall(S, d), \forall h \in \mathbb{R}^n : F(S + h, d + h) = F(S, d) + h$
5. Individual Monotonicity: Consider two bargaining problems (S_1, d) and (S_2, d) such that $S_1 \subset S_2$, and the range of attainable utility by any player j is same in both (S_1, d) and (S_2, d). Then individual monotonicity implies that utility of player $i \neq j$ is higher

in (S_2, d). In other words, an expansion of the bargaining set in a direction favorable to player i always benefits i.

KSBS suits our problem formulation because of its *individual monotonicity axiom*, which is further detailed in the later sections.

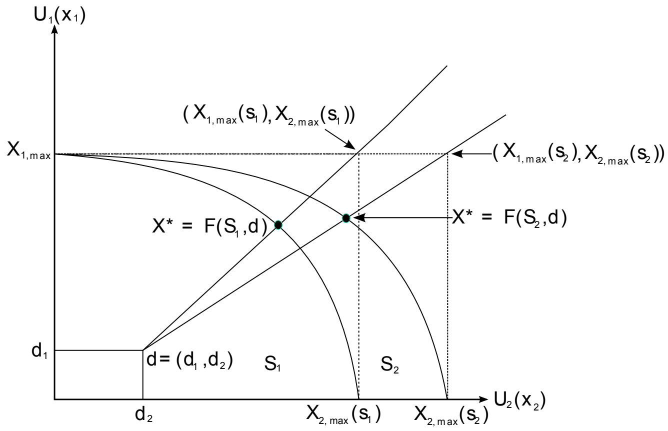


Figure 5.1: Illustration of axiom of individual monotonicity - The two axes in the figure represent utilities of two players, as can be seen that the player represented by x-axis increases her utility without effecting the utility of the other player. The increase the in the utility is consequence of an extended feasible set in the direction of x-axis player, in the proposed bankruptcy based problem formulation, such extension of feasible set is caused by an increase in the amount of offered bandwidth.

This can be illustrated in the Fig 5.1, which is plotted for two players. Keeping utility of one player fixed and increasing the utility of second player results in two feasibility sets S_1 and S_2 such that $S_1 \subset S_2$. In this case player 1 will attain the same utility in both sets however player-2 will attain more utility in set S_2 than in set S_1, therefore as a consequence of individual monotonicity axiom $KSBS$ will always allocate more utility to player 2.

5.2.4 Network Technologies and Characteristics

In this section, we elaborate on characteristics of the heterogeneous wireless technologies that we consider in this work.

5.2.4.1 LTE

LTE is built on an all-new radio access network based on Orthogonal Frequency-Division Multiplexing (OFDM) technology with higher order modulation schemes such as 64 Quadrature

Amplitude Modulation (QAM) and sophisticated Forward Error Correction (FEC) schemes, alongside complementary radio techniques like Multiple Input Multiple Output (MIMO) and Beam Forming with up to four antennas per station. In the downlink, it has the theoretical maximum of $300Mbps$ and minimum of $100Mbps$ per $20MHz$ of spectrum, whereas the theoretical uplink rates can reach up to $75Mbps$ per $20MHz$ of spectrum. LTE performs optimally in a cell radius of up to 5km, however it still can deliver effective performance in cell sizes of up to $30km$ radius. LTE is very flexible and can be deployed in various frequency bands using a mixture of channel bandwidths (1.25, 1.6, 2.5, 5, 10, 15, 20 MHz). Achievable data rate depends on provided bandwidth and MIMO technology. Considering minimum requirements of 5 bps/Hz in downlink and 2.5 bps/Hz is uplink, one can calculate supported data rates for following allowed BWs. The size of MAC frames, the *Transport Blocks* is decided by the MAC scheduler.

5.2.4.2 WLAN 802.11g

We consider IEEE 802.11g with Distributed Coordination Function (DCF). 802.11g operates at a maximum physical layer bit rate of $54Mbps$ exclusive of forward error correction codes, or about $22Mbps$ average throughput. Although 802.11g does not provide QoS guarantee, we assume that bottleneck is the transport network and we apply Diffserv there i.e., given $\sim 22Mbps$ WLAN throughput, the backbone network is based on a DSL link of 8Mbps.

5.2.4.3 UMTS

We consider the UMTS cellular network with data rates up to 2Mbps in small-cell outdoor environments (or in indoor environment), that uses Wide Band Code Division Multiple Access (WCDMA) technology for UTRAN air interface. WCDMA operates in Frequency Division Duplex (FDD) mode, where the given data rate is achieved with spreading factor 4, parallel codes (3 in downlink and 6 in uplink, 1/2 rate coding), frame length of 10ms (38400 chips).

5.3 Model and Assumptions

We consider an overall area $A = \{a_1, \ldots, a_L\}$ in a telecommunication coverage landscape L, consisting of an arbitrary collection of coverage areas of various access technologies, as demonstrated in Fig. 5.2. These access technologies exhibit different service capabilities i.e., they differ in bandwidth capacity, coverage and other characteristics (as given in Section 5.2.4).

We assume that these network technologies have two capacity regions, namely *congested* and *uncongested* regions. A network technology is said to be in congested region if its current available bandwidth drops below some threshold value O_{th}. The congested network behaves different from an *uncongested* one when offering resources to any application request and this behavior is determined by the *load balancing factor*, as we elaborate more on in the next section. We assume that there are a number of application users present in various coverage areas mentioned above. These users are generating bandwidth requests for applications of different service classes using *poisson distribution* and depending on these service classes network technologies offer different predefined amounts of bandwidth (following different operator policies as detailed in Section 5.3.1) to the application requests. Users' applications occupy different amounts of bandwidth capacities of network technologies for some amount of time (holding time) and users leave after staying connected for some random interval and release the resources. To have a realistic model of cellular networks, we also assume that users are mobile and move from one area to the other, resulting in variable number of serving network technologies at different times for the same application request.

5.3.1 Operator Policies for Offered Bandwidth

We assume that future telecom operators will employ various policies for offering bandwidth to the users. Hence the predefined offered bandwidth of an operator is assumed to be the function of operator policy denoted by π. The operator policies are strictly operator specific and are the elements of a finite operator policy set $\Pi = \{\pi_1, \ldots, \pi_z\}$. Here we describe a few different operator policies that we expect will commonly be adopted by the future operators.

1. π_p - supply the available capacity of a network technology $\tilde{c}_w$ as the offered bandwidth. We term such a policy as *potential-based* policy hereafter.

2. π_h - supply the strict values (operator defined) as offered bandwidth. We term such a policy as *hard-coded* policy hereafter. In such settings operators are enabled to define preferences over the association of services to the specific network technologies, which dictates that *flow splitting* is feasible over the whole operator capacity (both congested and uncongested regions). An example of offered bandwidth using π_h is shown in Table 5.1. As can be observed, operator controls the flow split by varying the hard-coded bandwidth offers; however, as soon as the network technology gets into congestion region, the offered bandwidth is derived by using Equation (5.3).

3. π_{co} - supply the service specific offered bandwidth (operator defined) unless the network congestion region is reached. We term such a policy as *congestion-based* policy hereafter. In this policy the operator avoids the flow splitting unless any of the network technology in a coverage area gets into congestion region, in which case the flow is split and load is shared among the available technologies. As long as the operator is in uncongested state, the operator defines priorities over the application association to the available technologies, e.g. i) audio $\rightarrow$ UMTS, WLAN, LTE, ii) video $\rightarrow$ LTE, WLAN, UMTS, and iii) data $\rightarrow$ WLAN, LTE, UMTS.

Table 5.1: Offered bandwidths based on operator policies for video application *(Network capacities in kbps)*

π	LTE	WLAN	UMTS	Flow splitting
π_h	500	200	600	Yes
π_p	$\tilde{c}_{LTE}$	$\tilde{c}_{WLAN}$	$\tilde{c}_{UMTS}$	Yes
π_{co}	1000	00	00	No,unless congested

The offered bandwidth for π_p is straightforward i.e., $\pi_p = \tilde{c}_w$, however when implementing the other policies π_h and π_{co}, it is expected that at some stage (when the operator is in congestion region) the network technology might not offer the operator defined bandwidth, thus in such case a tuned bandwidth is offered, which we term as *offered bandwidth* and is given as follows:

$$b_{k,c,w}(\pi_{co} \vee \pi_h) = \begin{cases} b_{k,c,w}(\pi_{co \vee \pi_h})\psi & \text{if} \quad w \in \overline{W}^a \\ b_{k,c,w}(\pi_{co \vee \pi_h}) + \frac{\tilde{c}_w}{\tilde{C}^a}\omega & \text{if} \quad w \in W^a \\ \tilde{c}^a_w \text{ if } \parallel W^a \parallel = 0 \end{cases} \tag{5.3}$$

where $\psi = e^{\frac{-l_w}{\tilde{C}_w + l_w}}$ and $\omega = \sum_{w \in \overline{W}^a} b_{k,c,w}(1 - \psi)$.

The load balancing factor ψ (160) is used to tune downward the operator offered bandwidth in case any network gets into congestion region. The offered bandwidth of an uncongested network is increased (tuned upward) by an amount that is equal to the sum of proportional bandwidth allocated to all those portions of request that could not have been supported by congested networks.

5.4 Cooperative Game Theoretic Resource Allocation

In cooperative games(165) players cooperate, form coalitions, and bargain with each other to reach an agreement of mutual benefits as opposed to non-cooperative games. In our formulation of radio resource allocation problem as a cooperative game, different network technologies in any coverage area covered by a number of network technologies bargain over the bandwidth requests generated by users for different applications, where each access network has its own *utility function* as detailed in Section 5.4.1. The utility function of network technologies is derived from the bandwidth that these network technologies allocate to any application request above the disagreement point. The disagreement point can be defined as the minimum desired utility that each network expects by joining the game without cooperation. We formulate the *bandwidth resource allocation problem* as the bankruptcy problem and to find the utility distribution rule (allocation of resources), we use the well-suited game theoretic approach *Bargaining* and a well-known bargaining solution KSBS.

5.4.1 Network Utility Function

We assume that network utility function is strictly increasing in the offered bandwidth, however offered bandwidth is driven and bounded by the operator policies:

$$u_w(b_{k,c}(\pi_z)) = \begin{cases} \tilde{\mu}\lambda & \text{if} \quad b_{k,c} \geq \pi_z \&\& \lambda = 1 \\ b_{k,c} & \text{if} \quad w \in \overline{W}^a \\ 0 & \text{if} \quad \lambda = 0 \end{cases} \tag{5.4}$$

where the decision boolean λ takes the value of 1, when the call is admitted and 0 otherwise. The component $\tilde{\mu} \cdot \lambda$ provides the basis for load sharing by network technologies, where $\tilde{\mu}$ may be equal to or greater than $b_{k,c}$.

5.4.2 Operator Utility Function

Operator aggregated utility can be defined as

$$\nu_p(\pi_z, B_{k,c}) = \begin{cases} r_{k,c} \times (pr_{w,k,c} - ch_{w,k,c}) & \text{if} \quad r_{k,c} \leq B_{k,c} \\ 0 & \text{otherwise} \end{cases} \tag{5.5}$$

where $B_{k,c} = \sum_{w \in (\overline{W}^a \cup W^a)} b_{w,k,c}(\pi_z)$, pr represents the operator pricing scheme. Given any pricing scheme, the operator utility increases in offered bandwidth. The utility component $pr_{w,k,c} - ch_{w,k,c}$ of the utility function motivates the operator to implement different policies.

Proposition 4. *The network technologies are motivated to share the load of congested network technologies, by increasing their offered bandwidth within π_h and π_{co}.*

Proof. Combining the network utility function in (5.4) with the operator utility in (5.5) dictates that the network technologies aggregated offered bandwidth when faced with a condition $B_{c,k} < r_{c,k}$ would result in $zero$ utility, which is further translated into $zero$ utility of network technology. Therefore network technology strives to achieve $B_{c,k} \geq r_{c,k}$ as long as the total aggregated capacity of network technology(ies) is greater or equal to requested bandwidth. Given the arguments, the result follows. □

5.4.3 Problem Formulation

To define the bargaining problem for the resource allocation bankruptcy problem, we start by defining the *feasible utility set*. Let the user $k \in K$[1] generate bandwidth requests $r_{k,c}$ for application class c in an abstract coverage area a covered by various network technologies. Upon receiving the request, the operator is made available with the necessary information[2] about the network technologies $w \in \{W^a, \overline{W}^a\}$. Given $r^a_{k,c}$ and $B^a_{k,c}$ for each possible value of k, c, and a, the bargaining problem is a pair $(S(r^a_{k,c}, B^a_{k,c}), d)$, where $S \subset \Re^n$ is a compact and convex set, such that

$$
\begin{aligned}
S(r^a_{k,c}, B^a_{k,c}) = &\{x^a_{k,c} \in \Re^n_+ \mid x^a_{k,c} \leq B^a_{k,c}, \\
&\sum_{w \in (W^a \cup \overline{W}^a)} x^a_{w,k,c} \leq r^a_{k,c}\}
\end{aligned}
\tag{5.6}
$$

$B^a_{k,c}$ is driven by the operator policies (refer to Section 5.3.1), the operator then distributes the request amongst the technologies by implementing the *request distribution algorithm* (detailed in Section 5.4.5). The consequence of the distribution algorithm is the bandwidth allocation by the network technology to the request. The objective of the resource allocation problem is to find out the amount of optimal resource allocation $x^*_{w,k,c}$ to the generated request. $d = (d_1, \cdots d_n) \in \Re^n$ is a given disagreement point. S represents the set of all possibilities of allocating bandwidth to the request, for which the available networks are bargaining over. However the allocation should not exceed the requested bandwidth. Each network technology within the coverage area allocates offered bandwidth to the requests when the networks in

[1] We assume that there exist three different user types namely i) Excellent - more sensitive to application quality, ii) Good, and iii) Fair - more sensitive to service costs (details available in Chapter 2).

[2] This information includes the current load, available bandwidth capacity, offered, and pre-defined offered bandwidths of the base station(network technology)

coverage area are all in the uncongested region, but the network technologies will offer tuned bandwidth when they are in the congested region. However, in such a situation the load of congested networks is shared by uncongested network technologies present within the same coverage area[1]. Therefore, our resource allocation management should satisfy the conditions in 5.7 and 5.8,

$$\sum_{a\in L} r^a_{k,c} \leq \sum_{w\in \bigcup\limits_{a\in L}(W^a \cup \overline{W}^a)} b^a_{k,c,w} \leq \sum_{w\in \bigcup\limits_{a\in L}(W^a \cup \overline{W}^a)} \tilde{c}_w \tag{5.7}$$

$$\sum_{w\in(W^a \cup \overline{W}^a)} b^a_{k,c,w} = \sum_{w\in(W^a \cup \overline{W}^a)} x^*_{w,k,c} \tag{5.8}$$

Setting the value of disagreement point d in our bargaining problem associated with bankruptcy problem $(S(r^a_{k,c}, B^a_{k,c}), d)$ influences cooperation among access technologies. The existence of a disagreement point is natural, since it endows one with a reference point from where utility comparison can be made. The problem with disagreement point is that there is no universally accepted criterion to select it (166). However selection of disagreement point in this work is influenced by the objective of simultaneous allocation of resources, which requires that all the available network technologies in the coverage area should participate in a game. Therefore, in this work, we keep the disagreement point as $zero$ which means that all network technologies will have utility equal to $zero$ if they do not collaborate. This also realistically represents the situation for different RATs of a single network operator.

5.4.4 Application of KSBS to the Bankruptcy Problem

Let the solution of KSBS x^* be given by

$$x^*_{k,c} = f^{ks}(S,d) \tag{5.9}$$

where

$$f^{ks}(S,d) = d + \tilde{\mu}^{ks}(X_{max} - d). \tag{5.10}$$

Here $\tilde{\mu}^{ks}$ is the maximum value of μ such that $d + \tilde{\mu}(X_{max} - d) \in S$ and X_{max} is the ideal point. Since the disagreement point in our formulation is $zero$, the problem reduces to:

$$f^{ks}(S,d) = \tilde{\mu}^{ks}(X_{max}) \tag{5.11}$$

[1]This is implemented by the operator policies detailed in Section 5.3.1

where X_{max} in our formulation is analogous to the offered bandwidth. For simplicity, consider the *two creditors* bargaining problem, the ideal point for this problem is then defined as $(b^{w_1}_{max}, b^{w_2}_{max})$, where $b^{w_1}_{max}$ and $b^{w_2}_{max}$ are the coordinates of ideal point. Given the ideal point, (5.11) for this problem becomes

$$f^{ks}(S,d) = \tilde{\mu}^{ks}(b^{w_1}_{max}, b^{w_2}_{max}) \tag{5.12}$$

the unknown quantity in (5.12) dictates the solution, which will be implemented by the *request distribution algorithm.*

Lemma 2. *The recommendations made by KSBS, when applied to 0-associated bargaining problems, coincides with the recommendation made by the proportional distribution rule.*

Proof. Let $x^*_{w_i} \forall i \in \{1,2\}$ represent the coordinates of the vector x^*, the optimal allocation. These coordinates are indexed by the operator technologies, which satisfies the requirements of feasibility set i.e., $x^*_{w_i}$ reside in the compact and convex feasibility set 'S'. Let us assume that *ideal point* for two player case is given by $X(b^{w_1}_{max}, b^{w_2}_{max})$, then the problem would be to minimize the distance between optimum point (allocation) and ideal, which is illustrated as follows:

$$\begin{aligned} min_{x^*_{w_1},x^*_{w_2}} \Bigg(\sqrt{(x^*_{w_1})^2 + (x^*_{w_2})^2} \; + \\ \sqrt{(b^{w_1}_{max} - x^*_{w_1})^2 + (b^{w_1}_{max} - x^*_{w_2})^2} \Bigg) \end{aligned} \tag{5.13}$$

as $x^*_{w_2}$ can be written in terms of $x^*_{w_1}$ i.e., $x^*_{w_2} = r_{c,k} - x^*_{w_1}$. Plugging this value in (5.13), we get

$$\begin{aligned} min_{x^*_{w_1}} \Bigg(\sqrt{(x^*_{w_1})^2 + (r_{k,c} - x^*_{w_1})^2} \; + \\ \sqrt{(b^{w_1}_{max} - x^*_{w_1})^2 + (b^{w_2}_{max} - (r_{k,c} - x^*_{w_1}))^2} \Bigg). \end{aligned} \tag{5.14}$$

Applying the first order condition to (5.14), we have

$$\begin{aligned} \frac{-2(r_{k,c} - x^*_{w_1}) + 2x^*_{w_1}}{2\sqrt{(r_{k,c} - x^*_{w_1})^2 + (x^*_{w_1})^2}} + \\ \frac{-2(b^{w_2}_{max} - x^*_{w_1}) + 2(b^{w_1}_{max} - r_{k,c} + x^*_{w_1})}{2\sqrt{(b^{w_2}_{max} - x^*_{w_1})^2 + (b^{w_1}_{max} - r_{k,c} + x^*_{w_1})^2}} \end{aligned} \tag{5.15}$$

Minimizing the (5.15) for $x^*_{w_1}$, we get the optimum allocation i.e.,

$$x^*_{w_1} = \frac{b^{w_1}_{max}.r_{k,c}}{\sum\limits_{i=1}^{N} b^{w_i}_{max}}. \tag{5.16}$$

Thus the optimal solution coincides with the principle of proportional distribution, where the proportionality in our case refers to the allocation proportional to offered bandwidth. The solution corresponds to the proportional distribution (167). □

Equation (5.16) shows that the requested bandwidth is proportionally distributed among the available network technologies within their coverage area based on their offered bandwidth.

5.4.5 Request Distribution Algorithm

We develop our proportional bandwidth allocation algorithm based on Lemma 1, as described next. The amount of allocated bandwidth by network w in area a to the request of application of class c is given by

$$x^*_w[r^a_{k,c}] = \beta \times b_{k,c,w}(\pi_z) \tag{5.17}$$

where

$$\beta = \begin{cases} \frac{r^a_{k,c}}{B^a_{k,c}} & \text{if } \parallel W^a \parallel > 0 \\ \frac{r^a_{k,c}}{\tilde{C}^a} & \text{otherwise} \end{cases} \tag{5.18}$$

and β is a proportionate factor.

5.4.6 Call Admission Control

The call admission control procedure in our work depends on the amount of bandwidth available on all those networks available at that time. An application request is admitted only if the sum offered bandwidth (predefined and tuned) by all the networks within the coverage area is more than requested bandwidth. Hence the admission control scheme is expressed as follows.

$$x^*_w[r^a_{k,c}] = \begin{cases} r^a_{k,c} & \text{if} \quad r^a_{k,c} \leq \sum\limits_{w \in (W^a \cup \overline{W}^a)} b^a_{k,c,w} \\ 0 & \text{otherwise} \end{cases} \tag{5.19}$$

However for non-real-time applications, we assume that user requests represent the user subscribed bandwidth. In such a case, an operator not meeting the required level of bandwidth causes an irritated user. Hence blocking such a call is preferred operator strategy rather than adopting a strategy where the user is admitted but service is not guaranteed. This in turn helps the reduction in user churn rate in the long-term. This argument justifies the call admission also for non-real-time applications.

5.4.7 Area Handover

We also consider the resource allocation issue when the user is mobile. User of an application may change the coverage area as he moves, resulting in a varying set of available networks to the user at different instances of time, which is analogous to the variable population bargaining problem. A slightly modified version of our resource allocation algorithm for mobility also achieves our objective of proportional resource allocation in variable network scenario. Call admission control is performed for each movement of a user from his current coverage area to any destination coverage area, according to (5.19). The user then releases the portion(s) of bandwidth allocated by all those networks that were present in the previous coverage area but not present in current coverage area. The following algorithm explains this handover process:

$$x^{a_o \to a_{cu}}[r^a_{k,c}] = \begin{cases} r^a_{k,c} & \text{if} \quad r^{a_{cu}}_{k,c} \leq \sum\limits_{w \in (W^a \cup \overline{W}^a)} b^a_{k,c,w} \\ 0 & \text{otherwise} \end{cases} \tag{5.20}$$

and

$$\tilde{c}^{a_o}_w(t+s) = \tilde{c}^{a_o}_w(t) + x^{a_o}[r^a_{k,c}] \tag{5.21}$$

where a_o is the previous / old coverage area before the handover, a_{cu} is the current coverage area after the handover, t is the time before handover and $t+s$ after the handover. Equation 5.21 illustrates the release of resources to the old point of attachment.

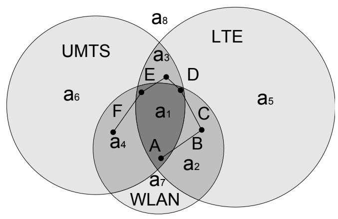


Figure 5.2: Network Scenario - We consider the scenario with telecommunication coverage areas defined by the heterogeneous wireless technologies owned by an operator. The trajectory highlights the movement of user under analysis in various coverage areas.

5.5 Numerical Analysis

In this section, we evaluate the proposed resource allocation approach in one operator and multi-technology scenarios.

5.5.1 Scenario Description

In this section we use a case study to assess the behavior of the proposed scheme. We consider the scenario with different areas covered by a various number of technologies as can be seen in the Fig.5.2. The access technologies include UMTS, WLAN, and LTE with bandwidth capacities $2Mbps$, $6Mbps$, and $20Mbps$ respectively (The high data rate of $20Mbps$ for LTE is chosen specifically to present the results more clearly, but it is still realistic considering the $40Mbps$ as its design goal.) Different coverage areas are defined in terms of network technologies that cover these areas:

1. $a_1 =$ UMTS, LTE, WLAN
2. $a_2 =$ LTE, WLAN
3. $a_3 =$ LTE, UTMS
4. $a_4 =$ WLAN, UMTS

For simulations, the arrival of requests is modeled by a Poisson process, and the service class is chosen randomly among voice, data, and video uniformly. The sizes of the requests are assumed to be static, and are 60 kbps, 300 kbps, and 450 kbps for voice, data, and video, respectively. After the distribution algorithms, the allocated bandwidths are subtracted from the bandwidth pools of the RANs, assuming that users have an infinite channel holding time. This allows us to simulate the overload conditions in the coverage areas. We first apply our proportional resource allocation scheme for three different operator policies, π_h, π_p, π_{co}, in a stationary setting, where all three network technologies are available for the entire duration of study (area a_1 in Fig. 5.2). The results are presented in Fig 5.3,&5.4, where the events on the horizontal axis effectively represent time instances for the arrival of application bandwidth requests. In Fig 5.3, the bandwidth amounts allocated by each available network to the applications are given, while the number of admitted and dropped calls are given in Fig. 5.4. Note that the values in Fig.5.4 are not instantaneous but cumulative; hence e.g., the adjacent repeating values for call drop mean that no call drop has occurred between the corresponding time events. We observe from Fig. 5.3 that a proportional amount of bandwidth is allocated to the requests based on the offered bandwidth of the network, which in turn depends on the operator policies. It can be observed that operator policies π_p and π_h behave in a similar fashion in terms of network utilization i.e., the load is distributed among different access technologies, saturating each technology around the same time. As soon as UMTS gets into the congestion region, it starts offering the tuned bandwidth and its load is shared by WLAN and LTE. After *event*-14, LTE starts sharing the loads of both UMTS and WLAN until its capacity is exhausted and call drops are observed after *event*-19 (see Fig. 5.4).

On the other hand the operator policy π_{co} results in different saturation points i.e., at *event*-1, *event*-5, and *event*-18 for UMTS, WLAN, and LTE, respectively. The impact of avoiding flow splitting during below congestion level can be analyzed by studying the call blocking. Call blocking in this case starts earlier i.e., *event*-14, as compared to other approaches, where the call blocking start at *event*-19. Furthermore a 29.5% decrease in active, and an increase of 38.2% in call blocking advocates the superiority of policies π_p and π_h over the policy π_h.

Remark 13. *An operator implements the congestion based policy if it is interested in avoiding flow splitting complexities or reducing the signaling cost involved in splitting flows.*

In order to analyze the behavior of our proposed algorithms with different operator policies in case of mobility, we consider different scenarios covering different situations of changes in the set of available access networks. This mobility scenario is depicted as a path labeled A to F in Fig. 5.2. We start with calls admitted in area a_1 and assume that the users of those applications move to area a_2. Since the three networks are already in congestion region, few call drops for policies π_h and π_p are observed as users move to area a_2, whereas about 17% more calls are blocked when operator implements π_{co}. This can be seen near the right edge of the region labeled as B in Fig. 5.6. No call drops are observed when the users move from a_2 to a_1, which can be observed by a straight line in the region labeled as C. In region D, users move from area a_1 to a_3 loosing the coverage of WLAN, which results in releasing bandwidth of WLAN and then WLAN gets out of the congestion region (see Fig. 5.5). LTE shares its load with UMTS as soon as UMTS is available when users move from area a_3 to a_1 as shown in region E, and no call drops are observed in this region. Now when the users move to area a_4, loosing the coverage of LTE, call drops are observed, inevitably. The resource utilization pattern in the mobile scenario pattern can be viewed in Fig. 5.5.

5.5.2 Comparison to Previous Approaches

We now try to assess the effectiveness of our resource allocation scheme in comparison to similar existing work in the literature. First, we provide comparisons with (1), where the authors

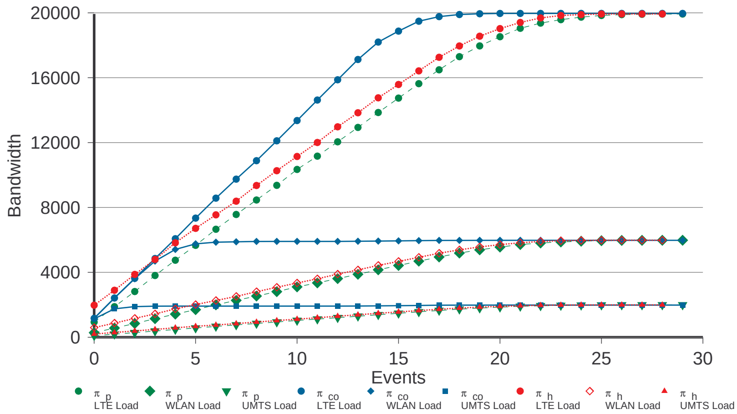


Figure 5.3: Resource allocation for three policies in area a_1 - Figure representing the resource utilization (implemented by the proposed approach) of heterogeneous wireless technologies.

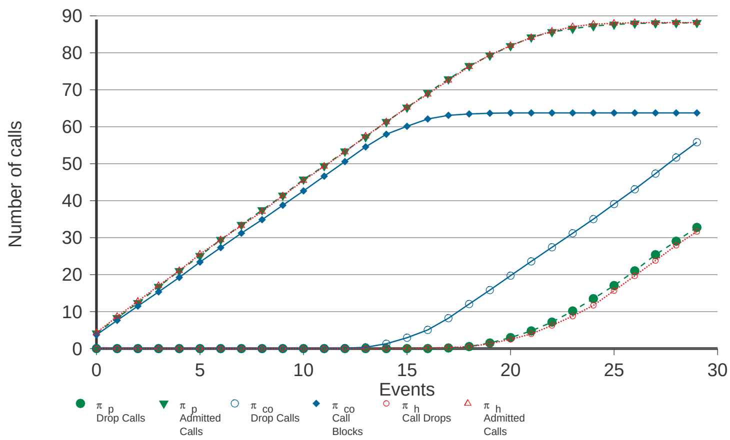


Figure 5.4: Number of active calls vs. call drops in area a_1 - Figure representing the number of accepted and dropped calls against different simulation events. The upper set of curves (the curves with non-zero values at event no.$zero$) represent the active calls, whereas the lower curves represent the number of blocked calls

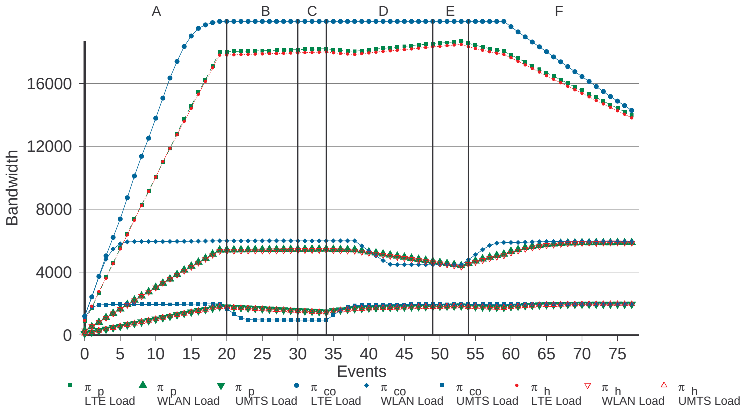


Figure 5.5: Resource allocation for three policies in mobile scenario - Figure representing resource utilization of heterogeneous wireless technologies in different coverage areas. The curves capture the resource utilization pattern in coverage areas with different capacities.

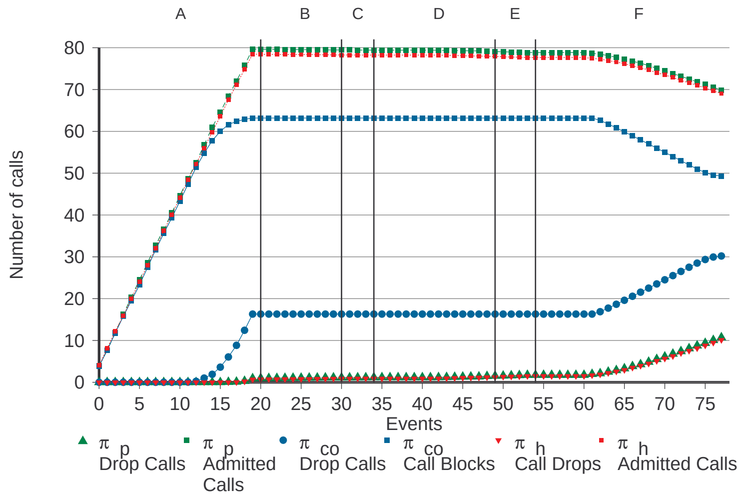


Figure 5.6: Number of active calls vs. call drops in mobile scenario - Figure representing the number of accepted and dropped calls against different simulation events. The upper set of curves (the curves with non-zero values at event no.$zero$) represent the active calls, whereas the lower curves represent the number of blocked calls

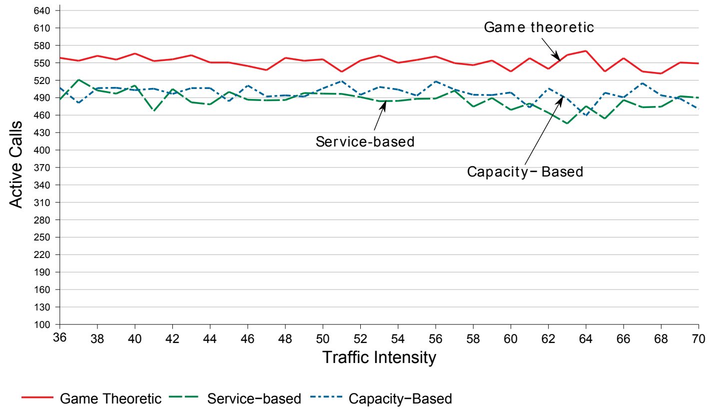


Figure 5.7: Number of Active Calls vs. Traffic Intensity (calls/min) - Figure representing the number of accepted and dropped calls against different simulation events. The upper set of curves (the curves with non-zero values at event no.$zero$) represent the active calls, whereas the lower curves represent the number of blocked calls

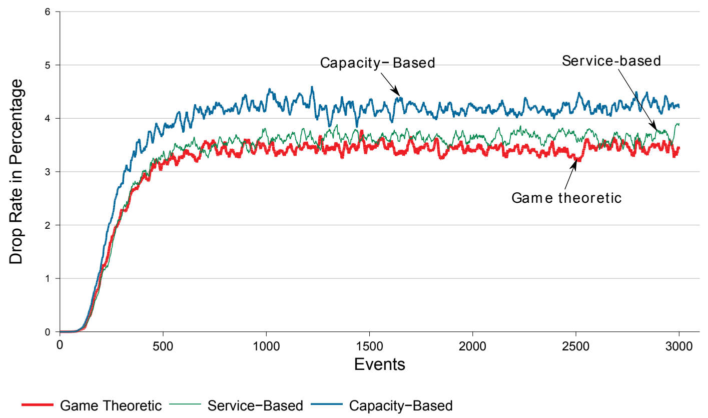


Figure 5.8: Call Blocking Probability vs. Simulation Steps - Figure representing the number of accepted and dropped calls against different simulation events. The upper set of curves (the curves with non-zero values at event no.$zero$) represent the active calls, whereas the lower curves represent the number of blocked calls

Table 5.2: Algorithm Parameters

Parameter	Value (1)	Value (2)	Value (1)	Value (2)
	GSM		WCDMA	
$b(voice1)$	12	120	32	150
$b(voice2)$	27	110	70	200
$b(data)$	48	300	123	50
CR	30	30	40	35

analyze the performance of their proposed schemes (LessVoice and Random) and other existing heuristics (First Fit, BestFit, WorstFit) in multi-access, multi-service environment in terms of call blocking probabilities. We use the same simulation parameters as used by the referred papers to obtain the call blocking probability using our approach. In addition, we set the values of additional parameters required in our scheme, namely predefined offered bandwidth, $b_{k,c,w}$, and congestion region threshold, CR_w, as given in the first column of Table 5.2.

Fig. 5.9 shows that the call blocking probability for our resource allocation scheme varies around 5 percent, and are both significantly less than the results presented in the referred paper for different algorithms with voice and elastic / non-elastic applications. Carefully tuning the parameters in our approach can result in even less call drop probability. We observe that there is a trade-off between the eventual call drop probability and the time call drops start increasing, as depicted in Fig. 5.9.

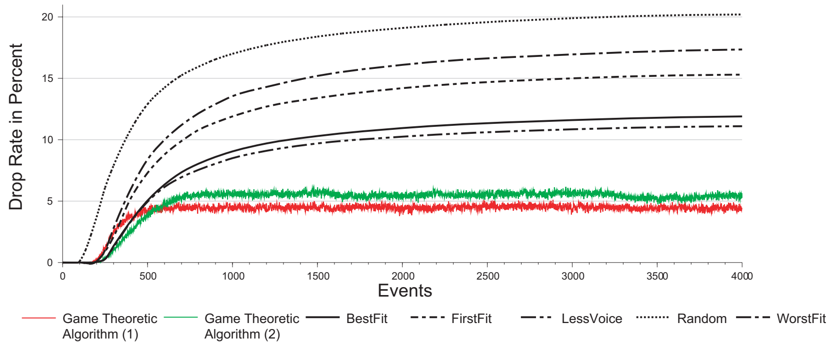


Figure 5.9: Comparison of our resource allocation scheme to those in (1) - As can be seen that the proposed approach outperforms various other approaches available in the research literature in terms of call drop rate

Change in performance of call blocking probability with different values of predefined offered bandwidth and congestion region threshold value is natural, as the amount of allocated bandwidth to request of bandwidth depends on predefined offered bandwidth. Network operators can control the allocation of bandwidth to any class of application by tuning predefined offered bandwidth and their control on the congestion region enable operators to always allocate some fixed amount of resources to application requests, until network congestion threshold value is reached and allocate less resources afterwards.

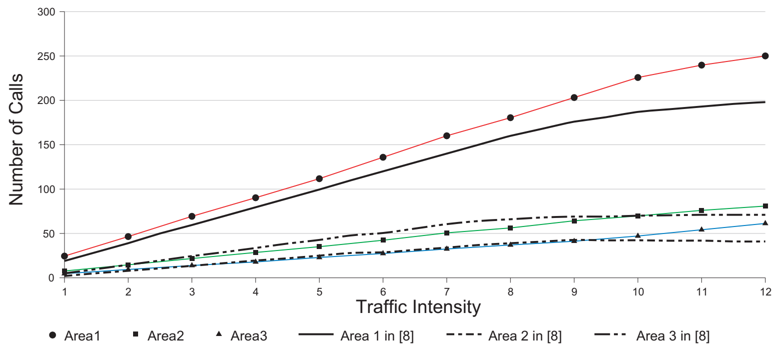


Figure 5.10: Comparison of our resource allocation scheme to that in (2) - The result curves indicate that the proposed approach accepts on average more calls in different coverage areas

As noted at the beginning of this chapter, (2) is very relevant to our work, as it also considers simultaneous use of multiple interfaces (as opposed to (1)) and also uses a collaborative game model with a different solution method for resource allocation. Thus we also compare the performance of our approach with (2), this time for average number of connections with unequal connection arrival rate. As the referred paper also discusses bandwidth splitting using cooperative games, we used the exact same parameters and simulated discretely for different areas using our resource allocation approach. The results are demonstrated in Fig. 5.10.

We also compare the the proposed approach to *service-based* and *capacity-based* approaches, for which we implement the allocation schemes as described in the *Introduction section*. The simulations are run in area a_1, which has the coverage of all access technologies. We compute the call blocking probability in area a_1 as a function of the simulation steps. We also plot the number of accepted requests as a function of traffic intensity in calls per minute, assuming a simulation time of 100 minutes. The results for these regions are given in Fig. 5.7 and Fig. 5.8. These results are compared with the results obtained by the *capacity-based* and *service-based* approaches discussed earlier. In the capacity based approach the players report their available bandwidths to the operator. The service request is then allocated to the RAN with the largest amount of free bandwidth. In the service-based approach, service classes are associated with certain RANs, and are allocated to other RANs only if the associated RANs are overloaded. In this scheme voice is allocated to GSM (implemented in simulation for this comparison), then to UMTS, and finally to LTE. Data is associated to UMTS, and allocated to LTE in overload conditions. For video the sequence is UMTS and then LTE. In this scheme the individual RANs submit the type of traffic they can support to the CRRM. CRRM chooses the RANs that are willing to support the service class of the request.

Our approach outperforms both the service-based and capacity-based solutions. In the area a_1, where only the we can support 12% more calls, with the same call blocking probability as the service-based approach.

5.6 Realization of the Proposed Flow Splitting Approach

The proposed approach of proportional flow splitting can be realized by implementing the Multiple Care of Addresses (MCoA) of Mobile IPv6 (MIPv6) as mentioned in RFC 5648. MCoA is employed for using various care of addresses simultaneously. In MIPv6 the Mobile Equipment (ME) registers its active interfaces with its Home Agent (HA) through MCoA registration mechanism and also instructs its HA by sending filter rules. HA starts intercepting ME destined traffic in its home network and sorts out, using filter rules sent by ME. This enables ME to use its various interfaces for receiving traffic simultaneously hence realizing our proposed splitting approach. In addition, *flow management identification* option in MIPv6 header is used to establish flow bindings between ME and HA/CN, just like a regular location update procedure used to inform receiver about the current location of ME. Moreover, the filter rules are also communicated using this flow binding. These flow bindings can be refreshed, removed, and can also get expired. A flow binding message is usually piggybacked on its associated CoAs binding message. In order to manage flows across available interfaces, another pair of extensions [6] can be used. The intrinsic problem in multi-path flow is the out of order packet delivery, which has adverse effect on TCP end- to-end performance and even some strictly delay sensitive applications. To avoid such TCP performance degradation, the solution in [7] can be employed.

5.7 Conclusion

In this chapter, we have presented a game theoretic approach for resource allocation using co-operative games, where available network technologies cooperate to simultaneously allocate resources to the application requests. The amount of allocation by each network technology is determined by a distribution rule that is found by applying Kalai-Smorodinsky Bargaining Solution to our resource allocation problem. Based on the distribution rule for resource distribution, we developed resource allocation, call admission and area handover algorithms and the proof of concept is presented by simulating our approach in different scenarios especially when users of applications are mobile. We also compared our approach with similar existing ones, demonstrating superior performance in terms of call dropping probability.

6

Network Centric Resource Allocation - Multi-operator Perspective

The current trend in wireless communication networks involves the integration of different wireless access technologies into a single operator network as detailed in Chapter 5. The possible leveraging of high deployment costs, and the possibility to increase revenue have also introduced the concept of network sharing between different operators. The problem of optimal allocation of bandwidth to multimedia applications over different wireless access networks, is augmented with the possibility of using the bandwidth of other operators who are willing to share bandwidth. In this connection, we extend the resource allocation approach of Chapter 5 to multi-operator resource sharing problem. We formulate the allocation of bandwidth within the operator network and distribution of excess bandwidth among operators as cooperative bargaining games. We provide distribution and allocation rules based on the Kalai-Smorodinsky Solution, and provide bandwidth offer algorithms based on these rules. We also compare this integrated approach with the service and capacity based approaches in the literature.

6.1 Motivation

Current business models of telecommunication operators are based on the concept of the so called *walled garden*: Service providers operate strictly closed infrastructures, and base their revenue-generating models on their capacity to retain current customers, acquire new ones, and effectively enact both technological and economic barriers to prevent users from being able to utilize services and resources offered by other operators. It is intuitive that the walled garden model prevents optimal re-use of the operators' under-utilized resources for non-profit or socially-oriented services, such as coverage of schools, public libraries, emergency forces, etc. The aforementioned network management practices are strongly rooted in the monopolistic history of the telecom operator industry. The liberalization of the operators has only changed the landscape in a way that there were multiple closed operators rather than one closed operator. This trend has had related implications on the network operator and the user side. Even with the current network management framework, the mobile networks still lack the seamless network access features. One obvious cause that one could think of is users' long-term contractual agreements with the operators. This in turn results in unsatisfied user pool. The potential candidate solutions to increase user satisfaction for the extended operator service(s) include; i) realizing the user-centric network selection, ii) planing the network deployment that it enables operators to meet user requirements in all the situations (such solution can be translated as over provisioning of resources, which is an expensive solution), and iii) Network load at the peak can be offloaded to other networks that have spare resources at that time.

It can be observed that network resource sharing is favorable solution. Such sharing of networks improves resource utilization while reducing provisioning costs. All the studies that apply game theory to CRRM mentioned in the research literature in Chapter 5 are confined to a single network operator scenario. A parallel development in the communications industry is the emergence of the concept of network sharing (118, 119), where operators share RANs to leverage investment, and to improve utilization of their investments. This however necessitates the extension of the concepts of CRRM to multi-operator scenarios, as well as coming up with techniques that deal with the interaction between the operators themselves.

In this chapter, we present such an integrated solution to CRRM management in a multi-operator scenario where the operators are in a network sharing agreement. We formulate the interaction in terms of two games, the intra-operator and the inter-operator games. In the former, the RANs belonging to an operator play a bargaining game to share the bandwidth of an incoming service request. If an operator needs extra bandwidth to support the service request, it does so by playing the second game with other operators, who share the bandwidth offered to the service request.

6.1.1 Model and Assumptions

We consider a coverage region R covered by various *radio access networks* (RAN) owned by different operators. The region R is divided into coverage areas a. An area is defined to be the geographical region which is covered by element(s) from the set of RANs. An area may be covered by a single RAN, by multiple RANs belonging to a single operator, or by multiple RANs belonging to multiple operators. We assume there are n different *Radio Access Technologies* (RAT) which are combined into RANs by the network operators, and m different operators. This topology is depicted in Fig 6.1. As can be seen that the figure details two hierarchical levels, where the players at the lower level are network technologies and operators reside at the upper level. We name these levels with respect to the players at them i.e., the lower level is termed as *network technology level* hereafter and similarly, we term the upper level as the *operator level*.

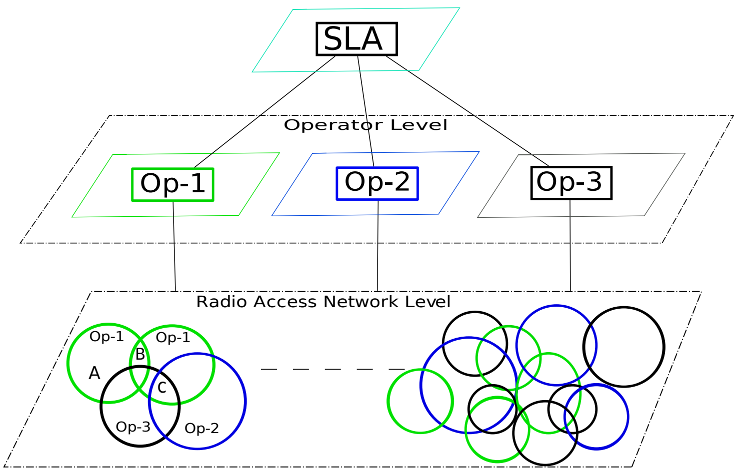


Figure 6.1: Different telecommunication players positioned at different hierarchical levels - The figure presents a bigger picture identifying different coverage areas in multi-operator multi-technology scenario

A consequence of network and operator level is the different definition of load and congestion for the RAN and area that is covered by different RANs:

1. RAN congestion: A RAN is said to be in *RAN congestion region* if its available bandwidth falls below some pre-defined threshold value.

2. Aggregated Congestion: An operator network is said to be in the *aggregated congestion region* in an area a if the aggregated available bandwidth of the RANs belonging to the

operator in this area falls below some threshold value.

We assume that users have contractual agreements with a *home operator* [1] and generate application requests of different QoS classes. We further assume that applications are partitionable meaning thereby that an application can run on multiple interfaces of different characteristics simultaneously. Upon initial access selection, which is not a part of this work, a user connects to the home network using some RAN belonging to its home operator first, and generates bandwidth requests for applications of different service classes. The home operator first allocates this bandwidth request to different *home* RANs in the area. We assume there is a functional CRRM entity that coordinates RANs of an operator in the area. If the operator is experiencing aggregated congestion in the area where the user is located, it will not allocate the bandwidth right away, but will request additional bandwidth from *foreign operators* which have RANs in the area, and are willing to share bandwidth. We assume that operators are in contractual agreements with each other to share resources, in terms of *Service Level Agreements* (SLA). The interaction between operators is monitored by a *SLA broker*, which is an independent neutral entity. After the interaction, the requested bandwidth is distributed among those operators who are willing to share bandwidth and their RANs are present in the area. Each operator treats its share of the bandwidth as a new bandwidth request.

The first step in which the requested bandwidth is shared between the RANs of the same operator is called the *intra-operator resource allocation*, and the second allocation step is called the *inter-operator resource distribution*. In this chapter we extend the resource allocation approach presented in Chapter 5 and (168), in which we formulate the intra-operator step as a bankruptcy problem and find the estate allocation to creditors using *Kalai-Smorodinsky* bargaining solution. Application of bargaining solution to bankruptcy problem is natural in that bankruptcy problems create the situation of conflict over distribution of estate and to resolve the conflict the creditors (players) negotiate to get to the point of agreement. Such negotiations are best framed using bargaining solutions. In this chapter, we also formulate the inter-operator game on the same lines and find the suitable utility distribution rule using KSBS. KSBS suits the multi-operator resource sharing problem formulation because of its *individual monotonicity axiom* (section 5.2.3).

[1] The operator that hosts the user related information database.

6.2 Cooperative Game Theoretic Resource Allocation

We use cooperative games to formulate the resource allocation management problem in multi-operator heterogeneous wireless networks at two levels. At the intra-operator level operator's RANs in an area bargain over the requests coming from users that belong to the operator. Executing intra-operator at this stage among the network technologies belonging to an operator over any splitable bandwidth request enable the operator to make optimal utilization of its bandwidth resource. The superiority of our intra-operator game in the context of bandwidth utilization is witnessed in our previous contribution (168). The request is *allocated* to different RANs, and the utility function of different RANs is set to be the amount of allocated bandwidth above a certain disagreement point.

If a bandwidth request cannot be fulfilled by the RANs of a home operator, the inter-operator game is played at *operator level*. The inter-operator resource *distribution* problem is formulated such that each operator present in a coverage area bargain over the excess bandwidth requests. The utility function is defined similar to the intra-operator case.

There are different sequences of these games being played according to the area in which a particular user is located. Different sequences are elaborated in Fig 6.1.

1. Area A: User is in his home network, and there is a single RAN. No games played.

2. Area B: User is in his home network, and there are multiple RANs belonging to the home RAN. Intra-operator game is played only.

3. Area C: User is in his home network, and there are multiple RANs belonging to multiple operators are available. Intra-operator game is played in the home network, followed by the inter-operator game if necessary. Intra-operator game is played once more in home and foreign networks with the new requests that result after the distribution by the inter-operator game.

We model the allocation and distribution problems as bankruptcy problems and obtain the utility distribution rules. These rules dictate the allocation of requested bandwidth to RANs and the distribution of excess bandwidth to operators. We employ well known game theoretic approach of *bargaining* and a well-known bargaining solution KSBS to come up with the allocation and distribution rules. The distribution rule is enforced by the SLA-broker, whereas the allocation rule is enforced by the CRRM manager. We also present algorithms that calculate the offers that the players in different games make, given the distribution rules. The choice of *KSBS* in our resource allocation and distribution problem formulation is dictated by its *individual monotonicity* axiom. As this enables any access network technology (in intra-operator game) or operator (in inter-operator game) to attain more portion of requested bandwidth by increasing their *offered bandwidth*. Hence providing operators with more control over utility maximization for specific technology(ies).

6.2.1 Bargaining Problem At The Intra-Operator Level

Let $r^a_{k,c}$ be the requested bandwidth of service class c in area a coming from the users belonging to operator $o \in \mathcal{O}$ where $\mathcal{O}$ is the finite set of the operators. Since the applications are partitionable and application requests can be allocated to different available network technologies within coverage area simultaneously, therefore playing intra-operator game the operator fairly allocates the application requests among their available network technologies. Furthermore, the operator o may have to serve bandwidth requests from other operator(s) in that area, which are in their aggregated congestion regions. These requests are denoted by $r^a_{k,c,\tilde{o}}$, where $\tilde{o}$ represents the set of operators in their aggregated congestion region. In such a case inter-operator game is played first, which results in distribution of different portions of excess bandwidth requests to cooperating operators, this game is then followed by intra-operator game among RANs of operators over the portion of requested bandwidth won by operator in inter-operator game. Together these requests form the vector $R^a_{k,c,o} = (r^a_{k,c,o}, r^a_{k,c,\tilde{o}}) \forall o \in \mathcal{O}$ & $\forall \tilde{o} \in \tilde{O}$, which represents the requests from a particular service class c belonging to home and foreign operators respectively that will be allocated to different RANs belonging to the home operator in this area. The RANs of that operator in the area a are members of the set $W^a_o = \{1, ..., n\}$.

$R^a_{k,c,o}$ is analogous to the estate of the bankruptcy game. The creditors of the game in turn correspond to the members of W^a_o. Each RAN $w \in W^a_o$ makes a bandwidth offer $b^a_{k,c,o,w}$. The resource allocation at this level is driven by the approach presented in the Chapter 5.

6.2.2 Bargaining Problem At The Inter-Operator Level

Let us formulate the inter-operator game on the same lines as presented in Chapter 5. Let $\bar{r}^a_{k,c,o}$ represents the excess bandwidth request for a service class c that an operator o cannot answer, and would like to offer in the inter-operator game to other operators, and the vector $\bar{R}^a_{k,c,o}$ represents all these requests from different operators in the region who are in aggregated congested regions.The operators play the game by making a bandwidth offer $b^a_{k,c,o}$, which can be grouped into the vector $\overline{B}^a_{k,c,o}$. The bargaining comes up with allocation of requested bandwidth to different operators, $x^a_{k,c,o}$, which should be a member of the compact and convex feasibility set:

$$S(\bar{R}^a_{k,c,o}, \bar{B}^a_{k,c,o}) = \left\{ x^a_{k,c,o} : x^a_{k,c,o} \leq b^a_{k,c,o}, \sum_{o \in \mathcal{O}} x^a_o \leq \sum_{o \in \mathcal{O}} \bar{R}^a_{k,c,o} \right\}$$

Let $\tilde{C}_o$ represents the aggregated capacity of operator o, that is calculated from the capacities of the RANs belonging to operator o in that area. Similarly the condition for the bankruptcy formulation is:

$$\sum_{o \in \mathcal{O}} \bar{r}^a_{k,c,o} \leq \sum_{o \in \mathcal{O}} b^a_{k,c,o} \leq \sum_{i \in \mathcal{O}} \bar{C}^a_o$$

Contrary to the intra-operator game the disagreement point $\bar{D}(c) = (d_1(c), \ldots, d_n(c)) \in \mathbb{R}^n$ is calculated from the bandwidth requests and offers of the operators. To depict the realistic scenario, we select the disagreement point as characteristic function in our bankruptcy problem at inter-operator level. The characteristic function of a bargaining problem is defined as the amount of utility conceded to a player by all other players. What this implies is that an operator will cooperate with other foreign operators if and only if the operator receives at least the amount of bandwidth not covered by the offers of the other operators. That is, for an operator o and foreign operators $\forall \grave{o} \neq o$ the disagreement bandwidth is given by:

$$d_{o,c} = max\{0; \sum_{o \in \mathcal{O}} \bar{r}^a_{k,c,o} - \sum_{\grave{o} \neq o} b^a_{k,c,\grave{o}}\} \tag{6.1}$$

Let the solution obtained by applying KSBS to our inter-operator bargaining problem be denoted by be denoted by $X^a_{o,k,c} = (x^a_{1,k,c}, ..., x^a_{o,k,c})$. Then

$$X^a_{o,k,c} = F^{KS}(S(\bar{R}^a_{k,c,o}, B^a_{k,c,o}), \bar{D}(c)) \tag{6.2}$$

The bargaining problem above is $\bar{D}$ associated bargaining problem in this case. Thus recommendations made by *KSBS*, when applied to $\bar{D}$ associated bargaining problem coincides by adjusted proportional distribution rule (167). In other words:

$$x^a_{k,c,o} = d_{k,c,o} + \frac{(b^a_{k,c,o} - d^a_{k,c,o})}{\sum_{o \in \mathcal{O}} (b^a_{k,c,o} - d_{k,c,o})} \cdot (\sum_{o \in \mathcal{O}} \bar{r}^a_{k,c,o} - \sum_{o \in \mathcal{O}} d_{k,c,o}) \tag{6.3}$$

This distribution rule is applied by the SLA broker.

6.2.3 Bandwidth Offer Algorithm at Intra-Operator Level

Here we present an algorithm for the individual RAN's given the proportional allocation rule. For each RAN, $\bar{b}^a_{k,c,o,w}$ is the pre-defined bandwidth offer associated with service class c, which is defined by the operators. If the current used bandwidth $l^a_{o,w}$ is larger than the *RAN capacity threshold*, described as a percent of the total capacity $C^a_{o,w}$ in a RAN, then the pre-defined bandwidth is scaled with the *load factor* $\psi^a_{o,w} = e^{\frac{-l^a_{o,w}}{C^a_{o,w}}}$, in order to find the bandwidth offer for that RAN.

As a result of this scaling, some of the RANs belonging to the same operator offer less bandwidth compared to the pre-defined values. Since they belong to the same operator, this represents a lower utilization of the operator resources. To overcome this problem, we allow the RANs that are not in the RAN congestion to share the aggregated difference between the pre-defined and actual offered bandwidths of the congested RANs proportionally to their own pre-defined bandwidths. In other words, let $\bar{W}^a_o \subset W^a_o$ be the set of congested RANs, then the algorithm for calculating the bandwidth offer $b^a_{o,w}$ is given by:

$$b^a_{k.c,o,w} = \begin{cases} \bar{b}^a_{k,c,o,w} \cdot \psi^a_{o,w} & \text{if } w \in \bar{W}^a_o \\ \bar{b}^a_{k,c,o,w} + \tilde{b}^a_{o,w} & \text{if } w \in W^a_o - \bar{W}^a_o \end{cases} \tag{6.4}$$

where $\tilde{b}^a_{w,o}$ stands for the proportional additional bandwidth that the uncongested RANs include in their offers, which is calculated by:

$$\tilde{b}^a_{k,c,o,w} = \frac{\bar{b}^a_{k,c,o,w}}{\sum\limits_{w \in W^a_o - \bar{W}^a_o} \bar{b}^a_{k,c,o,w}} \cdot \sum_{w \in \bar{W}^a_{k,c,o}} \bar{b}^a_{o,w}(1 - \psi^a_{o,w}) \tag{6.5}$$

Note that this algorithm requires exchange of information between individual RANs, which may be implemented by direct connection of RANs, through a central CRRM or a distributed CRRM as described in (117). Since the RANs belong to the same operator, this is a valid assumption.

6.2.4 Bandwidth offer Algorithm at the Inter-Operator Level

The algorithm for the operators turns out to be relatively simpler than the RANs, given the most actual bandwidth offers that the RANs made for a specified service class contain a considerable amount of information about the status of the operator network in an area. Specifically, the operator sums the most up-to-date bandwidth offers from the RANs in the area for the service class. Then this aggregated offer is scaled with the motivation factor of the operator $0 \leq \mu_o \leq 1$. By setting this factor, the operator is able to adjust the cooperative nature of its strategy. There is an incentive for cooperative behavior, as operators can allocate unused bandwidth to increase revenue and utilization. Thus:

$$b^a_{k,c,o} = \mu_o \cdot \sum_{w \in W^a_o} b^a_{o,w} \tag{6.6}$$

6.3 Results and Analysis

We simulate the proposed resource allocation approach in multi-hop scenario. The simulation environment consists of different coverage areas covered by different RANs of three operators. The network technology distribution among operators is as follows:

- Operator-1:WiMAX
- Operator-2: WiMAX, GSM
- Operator-3: WiMAX, WLAN, UMTS

We observe the gain of operator-2 for different levels of cooperation (for different values of motivation factor in our approach) and write it as *home operator* hereafter. The bandwidth requests of different quality classes are generated by users belonging to home operator using Poisson process with the mean 20. Simulation run is kept as 30 events, where events effectively present time instance for arrival of bandwidth requests. Simulation run for 30 events is justified here because of greater poisson process mean value. We consider three different cases here, i) When home and foreign operators are fully motivated to cooperate ($\mu = 1$ for all operators). We name this case as *fully cooperative* ii) When home operator and one foreign operator(Operator-1 in this case) are motivated to cooperate only, we name this case *selective cooperative* and iii) When no operators cooperate ($\mu = 0$), this case is called *non-cooperative case*. Results for *Fully cooperative* case can be seen in Fig. 6.2(a), where the home operator offers bandwidth to its users' requests until it gets into congestion, as can be seen at event-4 and onwards the excess load is shared by foreign operators. In this case no call drops are

Table 6.1: Predefined offer bandwidth

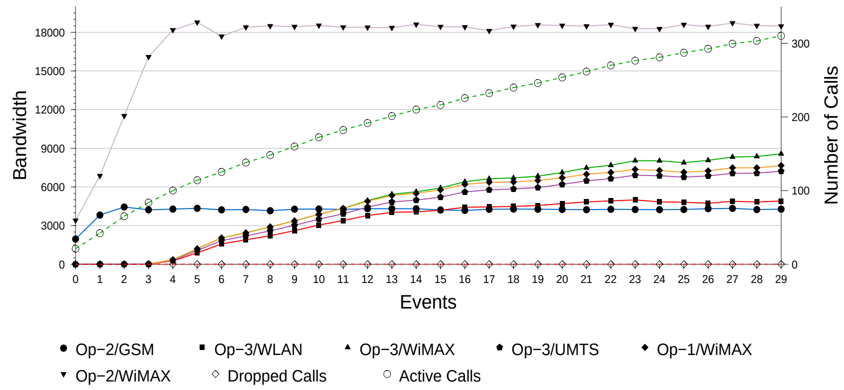
QoS Class	GSM	WiMAX	UMTS
Voice	500	240	400
Data	900	1000	800
Video	500	1600	500

observed. In *Selective cooperative case* Fig 6.2(b) although home operator gets into congestion very soon, but no call drops are observed unless cooperating foreign operator(operator-1 in this case) is congested from event 13 and onwards. Foreign operator-3 in this case is not motivated to bargain over the excess bandwidth requests by home operator. Coming to *Non-cooperative case* Fig 6.2(c), where greater call drop is observed since no foreign operator take part in the inter-operator bargaining. These results motivate operators to cooperate to achieve the objective function of satisfied and increased user pool cost effectively. Setting the value of motivation factor a foreign operator can make good use of his resources and increase revenue.

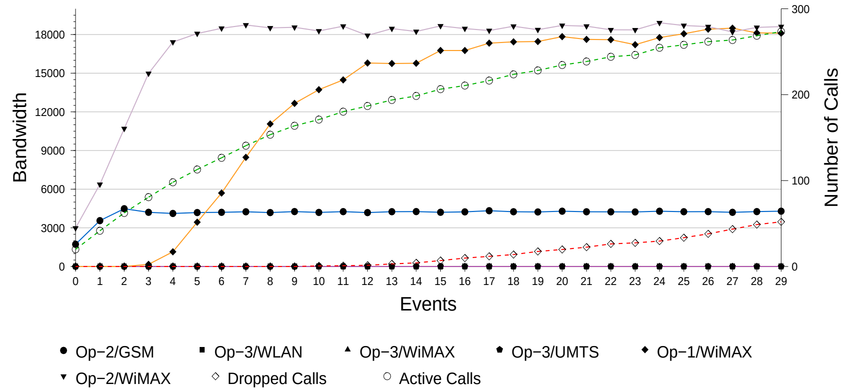
6.3.1 Comparison with other approaches

To assess the performance of our proposed approach compared to other approaches, we implement service-based and capacity-based allocation schemes as described in the Introduction section. We consider the simulation scenario given in Fig. 6.3, where simulations are run on area granularity $(a_1, \ldots, a_4)$ with service requests arriving for different types of applications.

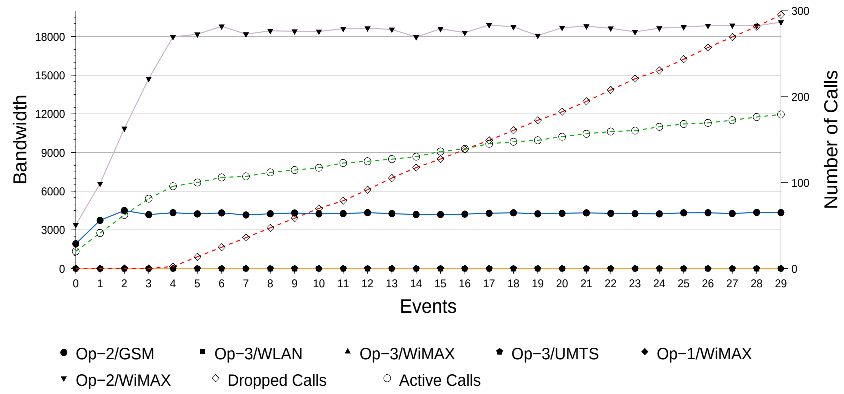
The arrival of requests is modeled by a Poisson process, and the service class is chosen randomly among voice, data, and video uniformly. The sizes of the requests are assumed to be static, and are 60 kbps, 150 kbps, and 500 kbps for voice, data, and video respectively. After the allocation and distribution algorithms, the allocated bandwidths are subtracted from the bandwidth pools of the RANs, assuming the users have an infinite channel holding time. This allows us to simulate the overload conditions in the areas, which results in inter and intra-operator games being played. We simulate a random topology with GSM, UMTS, and WiMAX. A GSM RAN has a capacity of 4500 kbps, UMTS 12000 kbps, and WiMAX 20000 kbps. The RAN overload thresholds are set to 10% for UMTS, GSM, and 3% for WiMAX. The operators share the same predefined offered bandwidth values in kbps, which are given in Table 7.2.



(a) Fully Co-operative



(b) Selective Co-operative (OP-1 cooperates with OP-2)



(c) Non-Cooperative

Figure 6.2: Network technologies bandwidth utilization and number of active calls for different settings of motivation factor

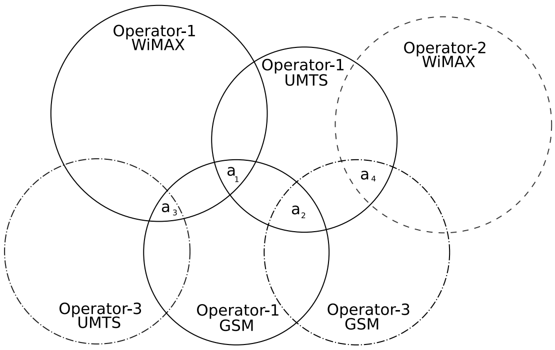
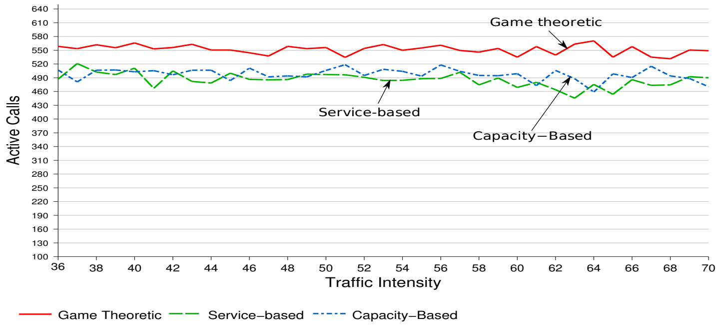


Figure 6.3: Simulation Scenario for comparison - The figure represents different coverage areas, we carry out simulation analysis for areas a_1 - a_4

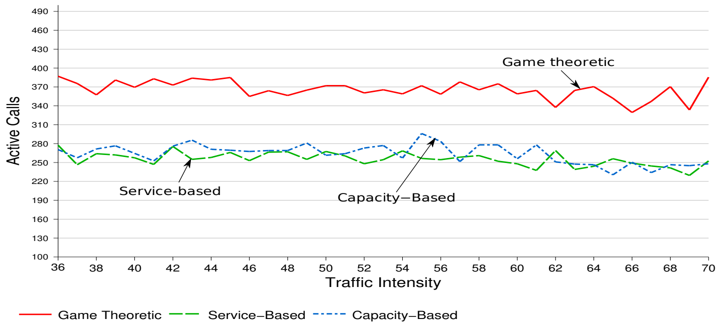
We then compute the call blocking probability in all areas a_1, a_2, a_3, and a_4 as a function of the simulation steps. We also plot the number of accepted requests as a function of traffic intensity in calls per minute, assuming a simulation time of 100 minutes. The results for these regions are given in Fig. 6.4 and 6.5. In area a_1, a single operator has RANs of all the possible RATs. In area a_2 operator-1 has UMTS and GSM, and the operator-3 has only GSM. In area a_3 operator-1 has deployed WiMAX and GSM, and operator-3 UMTS and in area a_4 operator-1 has UMTS, operator-2 has WiMAX and operator-3 has GSM, this is depicted in Fig 6.3.

These results are compared with the results obtained by the capacity-based and service-based approaches discussed earlier. In the capacity based approach the players report their available bandwidths to the SLA broker and the CRRM. The service request is then allocated to the RAN or the operator with the largest amount of free bandwidth. In the service-based approach, service classes are associated with certain RANs, and are allocated to other RANs only if the associated RANs are overloaded. In this scheme voice is allocated to GSM, then to UMTS, and finally to WiMAX. Data is associated to UMTS, and allocated to WiMAX in overload. For video the sequence is UMTS and then WiMAX. In this scheme the intra-operator game is played by individual RANs submitting the type of traffic they can support to the CRRM. CRRM chooses the RANs that are willing to support the service class of the request, and divide the requested bandwidth equally among these RANs. The inter-operator game follows the same lines by operators submitting the traffic class they wish to support to the SLA broker.

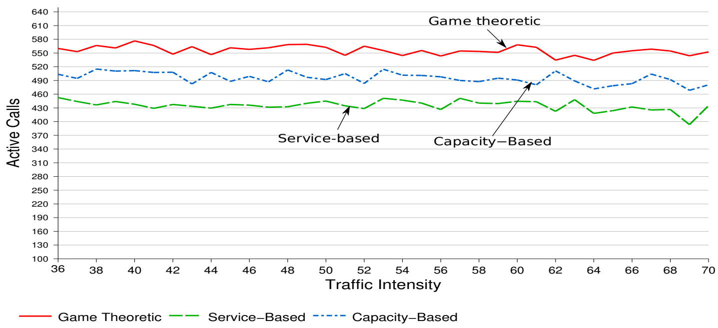
Our approach outperforms both the service-based and capacity-based solutions in all coverage areas. In the area a_1, where only the intra-operator game is played, we can support 12%



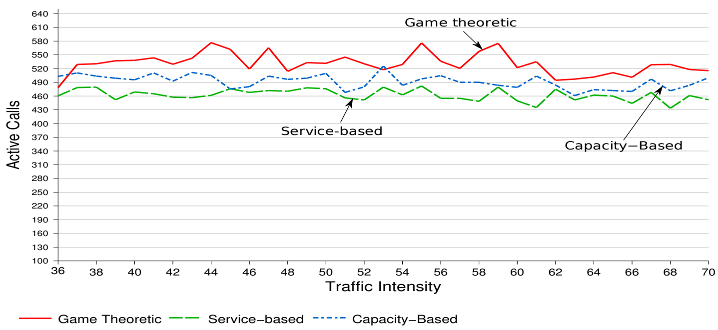
(a) Area a_1



(b) Area a_2

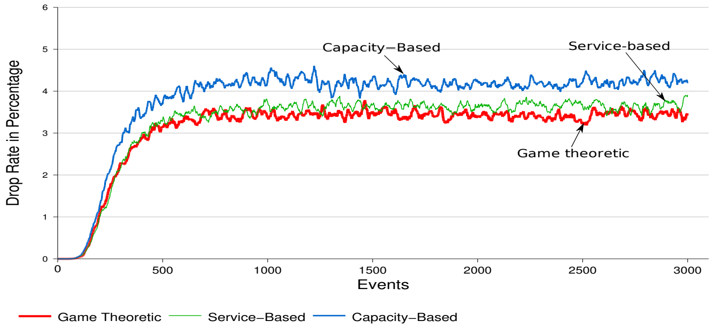


(c) Area a_3

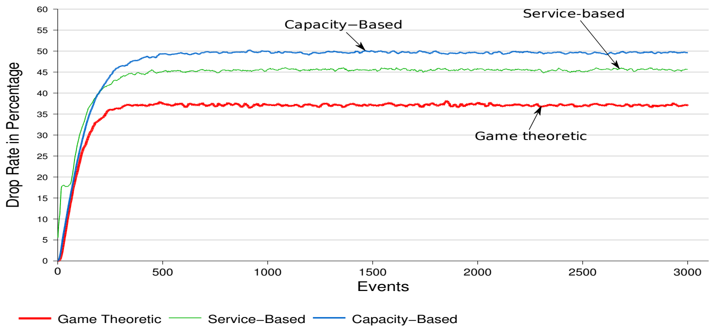


(d) Area a_4

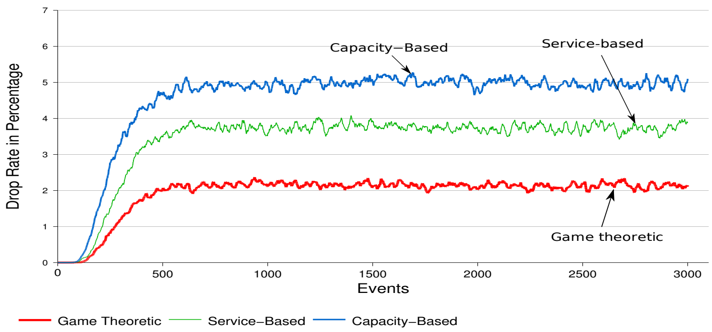
Figure 6.4: Number of Active Calls vs. Traffic Intensity (calls/min)



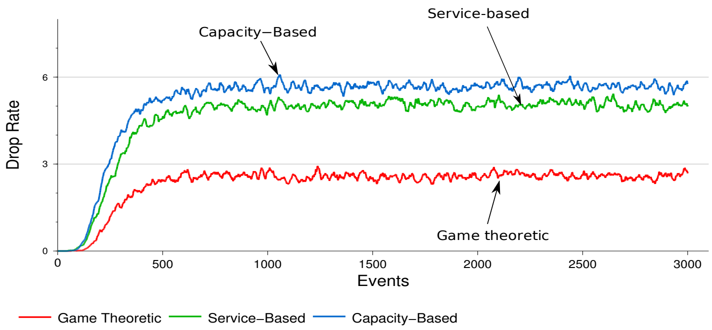
(a) Area a_1



(b) Area a_2



(c) Area a_3



(d) Area a_4

Figure 6.5: Call Blocking Probability vs. Simulation Steps

more calls, with the same call blocking probability as the service-based approach. In area a_2, where the operator-3 only has GSM, we allow operator-3 to make use of operator-1's UMTS and GSM, and are able to support 44% more calls, while reducing the call blocking probability from 45% to 36% . Note that this higher rate of call drop rate is due to the fact that operators have most GSM RANs, which has limited support for video or data requests. In the area a_3, where there is plenty of bandwidth to be shared in the inter operator game we outperform the service-based approach by 28% and the capacity-based by 11%. We almost halve the call drop probability compared to capacity- based scheme in the area. In area a_4 a somewhat similar behavior to the area a_1 is observed in terms of bandwidth utilization however we improve 50% in terms of call blocking probability. It is also important to note that compared within each other the capacity-based solution is able to support more calls, but has an inferior call blocking rate.

In the light of the results, we can draw the conclusion that our solution outperforms both of the compared approaches, and its virtue becomes more spoken when there is abundant bandwidth to be shared for better utilization as in area a_3, or when there is a asymmetry between the capacities of operators as in the case of area a_2.

6.4 Conclusion

In this chapter, we formulated the multi-operator CRRM problem from a Game Theoretic perspective, as a two level bargaining game. The CRRM manager within the operator networks employ an allocation rule to distribute the bandwidth requests from user applications among the operator RANs based on the offers that the RANs make. If the operator is in aggregated congestion in the region, and is not able to meet the bandwidth request, it makes an offer based on this request to the SLA Broker, which employs an distribution rule to distribute such offers among the participating operators in the area. Both of these rules are found by employing the KSBS solution to bargaining. We also presented two bandwidth offer algorithms to be implemented by the RANs and operators. We then compared out approach with service and capacity based rules and showed that it is able to outperform both in terms of number of active calls and call drop rate.

7

Performance Evaluation of Network Centric against User Centric Approach

In this chapter, we focus on comparing the performance of proposed network-centric resource allocation approach against the user-centric network selection in terms of resource utilization and call blocking probability and user received throughput. The purpose of the comparison is to study the impact of load sharing approach on operator's objective function in different configurations (user-centric and network-centric). This study also enables us to compare the performance of the proposed network-centric resource allocation approach to the other resource sharing approach available in the literature. This in turn evaluate how better can the proposed network-centric resource allocation work, when implemented in future user-centric paradigm.

7.1 Introduction

As we know that users in future wireless landscape are becoming more technology proficient and they expect dynamic and bandwidth hungry applications with various quality levels on their mobile wireless devices. The major players in future supply and demand cycle are users and operators. However, the market driver is the one that possess the controller. By the controller, we mean the freedom to decision of network selection at user-end or monopoly like resource allocation at the operator end. This dictates that one can define two major telecom market controllers namely; i) user-centric controller and ii) network-centric controller. We focus on these controllers with regard to network selection approach. In this connection, we differentiate the term network centricity from the user-centricity with respect to the conflicting objective functions of the users and network operators. The consequence of such differentiation is the two major performance measurement categories i.e., the performance measurement of the parameters relevant to network operator objective function and the performance measurement of user objective functions. In this chapter, we compare the gain of network provider (when the operator network system implements the proposed game-theoretic load sharing approach) against the users' gain (when the system implements proposed utility based user-centric network selection solution).

Remark 14. *It should be noted that performance analysis parameters are not similar in both the configurations e.g., the performance of the network centric resource allocation can be investigated by evaluating the call blocking rate, resource utilization, etc., whereas the evaluation of user satisfaction for operator extended services represent the users' gain. This dictates that to compare the two configurations, they need to be made comparable.*

7.2 Network-Centric Resource Allocation

We implement the resource sharing model presented in the Chapter 5.

7.3 User-Centric Multi-attribute Auction Based Network Selection

In this section, we present the user-centric network selection model. The model is simplified variant of the proposed user-centric network selection approach (refer to Chapter 3). We assume that users generate service requests of different application types (audio, video, and data) and defining their preferences over service quality for the requested application(s). Upon receiving a request for an application type, network operators available within the coverage area present service offers that satisfy the minimum application requirements, which are evaluated by the users' expected values of different parameters. Parameters include technology-specific, application-specific and user-specific preferences. Users select the network technology / operator for any application whose offer matches closest to the user expectations.

Now, we formally define the user-centric network selection model as a multi-attribute auction game using the *sealed bid second price Vickery* auction format. For game-theory basics specific to the problem formulation in this chapter, Chapters 5 & 3 can be referred. Let

$\mathcal{I} = \{1, \ldots I\}$ be the finite set of users and $\mathcal{O} = \{1, 2, \ldots, o\}$ be the finite set of network operators, w is the network technology in area a and $\{(r^a_{k,c} \mid k \in \mathcal{K}, c \in C\}$ be the user request within coverage area a, where C represent the set of application types, which in turn is characterized by different amount of required bandwidth resource. $\mathcal{K}$ characterizes the preference of user over the quality, which can be translated in the vector of various QoS attributes and expected ranges of these attributes for user request and $r^a_{k,c}$ is the required bandwidth by application of QoS class c. Intuitively, in the request, $r^a_{k,c}$ represent the upper bound on the preferred quality range (defined in the Table 7.1). In the proposed user-centric network selection model, *buyers* are analogous to *application users*, *sellers* to *network operators* of available network technologies within coverage area a and the *requested bandwidth* with associated attributes is considered as *auctioned item*. For any application request the user announces intention to acquire the item $r^a_{k,c}$ through the auctioneer residing on user terminal. It should be noted that $\mathcal{K}$ can be translated in the user types (i.e., excellent, good, and fair). Auctioneer broadcasts this request in the coverage area a, which is received by the operators owning network technologies in that area. Upon receiving this request the operator(s) submit their bids that identify the offer against the requested bandwidth.

The candidate operators create bids after they receive the *broadcasted* application bandwidth request by auctioneer in that area. Let the bid bi by operator technology w be $bi^a_{k,c,w,o}$, which is given by the tuple:

$$bi^a_{k,c,w,o}(r^a_{k,c}) = (r^a_{k,c}, \pi^a_{k,c,w,o}) \tag{7.1}$$

where $bi^a_{k,c,w,o}(r^a_{k,c})$ is bid offer from operator o through network technology w in an area a against the application required bandwidth $r^a_{k,c}$, associated attribute vector $k \in \mathcal{K}$. The associated attribute values can be the consequence of different user types, this is evident from different value ranges in Table 7.1. $\bar{\pi}^a_{k,c,w,o}$ is per unit bandwidth payment. Both users and network operators are characterized by their utility functions. The bid formation is dictated by the operator *utility function*. Framing this simply, we can say that the *bidding mechanism* is influenced by candidate operators' strategies that increase their payoffs, before we define the *utility function* of a network operator. let us assume that $D = max_{\{\bar{w},\bar{o}\neq o\}} bi_{\bar{w},\bar{o}}(r^a_{k,c}, \bar{\pi}_{\bar{w},\bar{o}})$ be the maximum suitable bid if operator $o \in \mathcal{O}$ does not participate in the game. We also assume that the value of every QoS attribute is the simple linear function of cost incurred by network operator, meaning thereby cost increases linearly with increasing value of any QoS attribute in the direction of improving QoS. We also know that the operator receives amount against its extended service(bandwidth in our case) on per unit basis. Thus the utility function of operator in user-centric network selection will be:

$$U_{w,o}(r^a_{k,c}) = \begin{cases} r^a_{k,c}\bar{\pi}^a_{k,c,w,o} - \sum\limits_{k\in\mathcal{K}} \bar{c}_{k,c,w,o} & \text{if} \quad D \leq bi^a_{k,c,w,o} \\ 0 & \text{if} \quad D \geq bi^a_{k,c,w,o} \\ \lambda r^a_{k,c}\bar{\pi}^a_{k,c,w,o} - \sum\limits_{k\in\mathcal{K}} \bar{c}_{k,c,w,o} & \text{if} \quad D = bi^a_{k,c,w,o} \end{cases} \tag{7.2}$$

where $c_{k,c,w,o}$ is the cost incurred on a single attribute value and we assume it to be the linear function of attribute values, meaning thereby increasing / decreasing the values of attribute that result in better user perceived QoS increases the network cost linearly. $\sum\limits_{k\in\mathcal{K}} \bar{c}_{k,c,w,o}$ is the operators' reservation price for service. λ is tie breaking co-efficient that can take any value $\{0, 1\}$ randomly.

It is straightforward to prove that the formulated auction is strategy proof, where each operator (bidder) maximizes its utility by bidding truthfully. The following lemmas follow from similar proof constructs given in (169, 170), which we omit here due to space restriction.

Lemma 3. *For every bid $bi^a_{w,o} \neq \widehat{bi^a_{w,o}}$ of an operator $o \in \mathcal{O}$ there is a bidding profile $bi_{\{-w,-o\}}$ of other operators such that $u_{w,o}(bi^a_{\{-w,-o\}}, bi^a_{w,o}) < u_{w,o}(bi^a_{\{-w,-o\}}, \widehat{bi^a_{w,o}})$, where $bi^a_{w,o}$ is operator o's bid with false valuation of request and $\widehat{b^a_{w,o}}$ represents the bid with true valuation.*

Lemma 4. *In the strategy proof auction and for any value of offered bandwidth and associated QoS attributes $(r^a_{k,c}, k) = argmax_{(r^a_{k,c},k)}((r^a_{k,c}, k)\pi^a_{w,o} - \sum\limits_{k\in\mathcal{K}} c_{w,o}(k))$ holds, where $(r^a_{k,c}, k)\pi^a_{w,o} \in \bigcup_{\mathcal{K}, r^a_{k,c}\in C}$ which maximizes bidder's utility based on payment $\pi_{w,o}$.*

We can express the network bids in the form of a matrix where rows represent the networks/operators and columns represent different attribute values, offered bandwidth and service payments of operators.

$$bi^a_{k,c,w,o}(r^a_{k,c}) = \begin{pmatrix} r^f_{k,c,1} & \zeta_{d_k,c,1} & \cdots & \zeta_{pl_k,c,1} & \bar{\pi}_{c,k,1} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ r^f_{k,c,w} & \zeta_{d_k,c,w} & \cdots & \zeta_{pl_k,c,w} & \bar{\pi}_{c,k,w} \end{pmatrix}$$

Here $r^f_{k,c,w}$ is the offered bandwidth by network w, $\zeta_{k,c,w}$ represent the normalized value of each associated attribute (explained later), as can be noticed that k is the index of different associated QoS attributes e.g., delay d_k or packet loss pl_k. $\bar{\pi}_{c,k,w}$ represents the payment per unit bandwidth over network w.

Winning bid is the consequence of user satisfaction. The degree of users satisfaction is translated using user utility function, which captures users' preference relationship over various QoS attributes and their behavior towards the amount of offered bandwidth. Since QoS attribute vector is n-dimensional, therefore user preference to every single attribute is represented by assigning weights to attributes. User evaluate amount of offered bandwidth and each relevant attribute quoted in the offer from network provider using its utility function(scoring function) and compute the utility of overall bid by using *weighted sum* over each utilities attained for each individual attribute and the utility obtained from the offered bandwidth as:

$$U_k(bi^a_{k,c,w,o}(r^a_{k,c})) = \frac{u_i(rk,c,w,o)}{\sum\limits_{k\in\mathcal{K}} \bar{\psi}_k \zeta_{k,c,o,w}} - \bar{C}_k(r^a_{k,c,o,w}) \tag{7.3}$$

where $\zeta_{k,c,w,o}$ represents the normalized value of each associated attribute $k \in \mathcal{K}$, ζ can be normalized in various expectancies i) the smaller the better, ii) the nominal the better, and iii) the greater the better. $\bar{\pi}_w$ represents the payment per unit bandwidth over network w, $\bar{\psi}_k$ is the user assigned weight to attribute k, and $u_k(r^f_{k,c,o})$ is the utility obtained by the offered bandwidth. The application utility is given by (171)(172)

$$u_k(r^f_{k,c,o}) = \begin{cases} 0 & \text{if } u_k(r^f_{k,c,o}) \leq r_{k,c,min} \\ u_0 + \alpha \frac{1-e^{-\bar{\beta}(r^f_{k,c,p} - r_{k,c,min})}}{1-e^{-\bar{\beta}(r_{k,c,max} - r_{k,c,min})}} & \text{if } r_{k,c,min} \leq u_k(r^f_{k,c,o}) \leq r_{k,c,max} \\ u_0 + \alpha & \text{if } r^f_{k,c,o} \geq r_{k,c,max} \end{cases} \tag{7.4}$$

where $r_{k,c,min}$, $r_{k,c,max}$ are minimum and maximum required application bandwidths respectively. u_0 is the private valuation of user, which in our case is the minimum application required bandwidth i.e, for any value of offered bandwidth that is less than minimum application required bandwidth, users' utility is equal to $zero$. A careful look at the utility curves in (173) reveals that utility is concave for different services like video, audio and data. The assessment of different weights to various associated QoS attributes are of prime importance for decision of optimal interface selection. Various proposed techniques that compute these weights include Analytical Hierarchy Process (AHP), Fuzzy sets, Multi-attribute Utility Theory (MAUT), Smart Multi-attribute Rating Technique (SMART) etc. $\bar{C}_k(r^a_{k,c,o,w})$ in (7.3) represents the cost of service paid by user in terms of price. Auctioneer evaluates the offered service price as $\bar{C}_k(r^a_{k,c,o,w}) = \frac{\bar{\pi}^a_{w,o}}{\bar{\pi}^{max}_k}$, where the user specifies her maximum valuation of the service through $\bar{\pi}^{max}_k$.

For a typical user it is difficult to describe technically the preferences over communication parameters for any application. This can be addressed by providing a Graphical User Interface

Table 7.1: QoS parameters and ranges

Codec	Parameters	Range	Score	Category
	70ms $\sim$ 100ms	10	Excellent	
Delay	100ms $\sim$ 150ms	8	Good	
	150ms $\sim$ 200ms	6	Fair	
	30ms $\sim$ 50ms	10	Excellent	
Jitter	50ms $\sim$ 60ms	5	Good	
	60ms $\sim$ 70ms	3	Fair	
	$\sim 10^{-6}$	10	Excellent	
Packet Loss	$10^{-6} \sim 10^{-5}$	7	Good	
Rate	$10^{-5} \sim 10^{-4}$	4	Fair	

Table 7.2: Predefined offer bandwidth

Class	GSM	WiMAX	UMTS
Voice	500	240	400
Data	900	1000	800
Video	500	1600	500

(GUI) to the users, as in (73), which takes the following inputs: i) service request class – *Data*, *Video*, *Voice*; ii) service preferred quality – *Excellent*, *Good*, *Fair*; iii) Service price preferences – *Always Cheapest*, *Indifferent*. Once these inputs are specified, they need to be translated into technical communication requirements. In this context, Table 7.1 (174) is used in order to map user defined *service preferred quality* to the technical communication parameters:

The auctioneer computes the wining bid from the matrix such that the wining bid maximizes the users' utility i.e., by Equation (7.3). Auctioneer also determines the price that user pays to the winning network operator for the service. However the costs posed by user-centric network selection solution in terms of frequent handover is addressed by using fuzzy logic and MOS value based approaches on the similar lines as explained in Chapter 3. .

7.4 Results and Analysis

In order to evaluate the approaches for both network-centric resource allocation and user-centric network selection, we simulate these approaches. In the simulation setup, various coverage areas are generated randomly. These coverage areas are covered by GSM, UMTS, and WiMAX RANs. We further configure the capacities of the RANS as; GSM RAN = 4,500 kbps, UMTS = 12,000 kbps, and WiMAX = 20,000 kbps. The RAN overload thresholds are set to 10% for UMTS and GSM, and to 3% for WiMAX. Users request generation is modeled by a poisson process, call holding time is exponentially distributed, and the service class is chosen randomly among voice, data, and video uniformly. The sizes of the requests are assumed to be static, and are 60 kbps, 150 kbps, and 500 kbps for voice, data, and video respectively. After the allocation and distribution algorithms, the allocated bandwidths are subtracted from the bandwidth pools of the RANs. The operators share the same predefined offered bandwidth values in kbps, which are given in Table 7.2. We now concentrate on the performance analysis of coverage area a covered by three technologies owned by three different operators, such that operator-1 has UMTS, operator-2 has WiMAX and operator-3 has GSM in the area.

To investigate the game-theoretic *network-centric resource allocation*, we assume that there are different number of users who have contractual agreements with different available operators. Users of each operator are assumed to generate service requests according to different poisson distributions with means $\bar{\mu}_{p-1}$, $\bar{\mu}_{p-2}$ and $\bar{\mu}_{p-3}$. For the network-centric allocation case, we simulate operators' strategies when they cooperate under under-utilized and in-congestion conditions, or when they are non-cooperative. We assume that the requests are generated using $\bar{\mu}_{p-1} = 2$, $\bar{\mu}_{p-2} = 1$, and $\bar{\mu}_{p-1} = 2$. Here we discern three cases based on different motivation factors of the involved operators. In the cooperative case all operators have a motivation factor of 1. In the selective cooperative case operators 1 and 2 have a motivation factor of 1, and operator-3 has a motivation factor of 0. In the non-cooperative case all operators have a motivation factor of 0. Fig 7.1 represents the non-cooperative case, which depicts

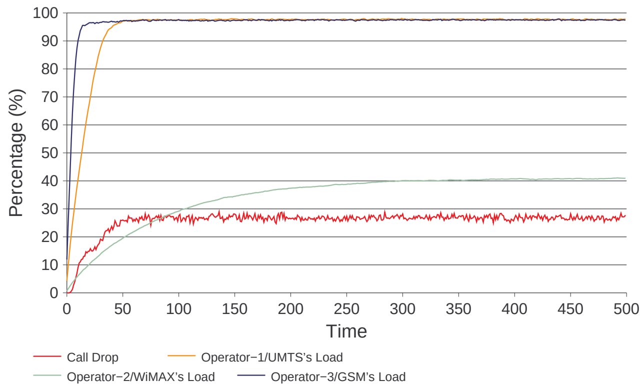


Figure 7.1: Non-Cooperative Scenario - Figure representing operators resource load and the aggregated call blocking percentage in non-cooperative operators' settings

that operator-2 is under-utilized and the aggregated call blocking is around 30% owing to the fact that all the operators are non-cooperative. In Fig 7.2, the selective cooperative case, call blocking is reduced by 30% and resource utilization of operator-2 is increased by almost 100% when compared with the non-cooperative case. In the fully cooperative case, as shown in Fig. 7.3, the aggregated call blocking percentage is reduced to almost 10% whereas the resources of all operators in the area are fully utilized. This demonstrates the performance of proposed

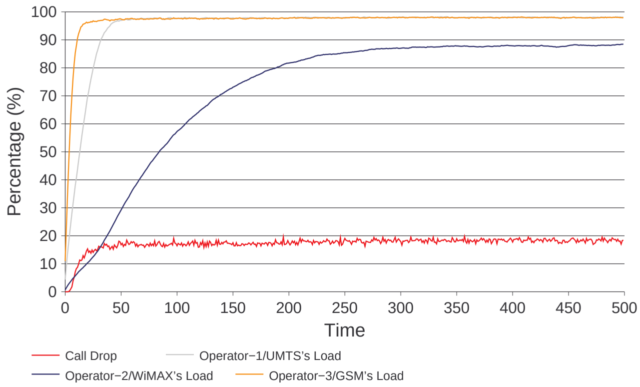


Figure 7.2: Selective Cooperative Scenario - Figure representing operators resource load and the aggregated call blocking percentage in selective cooperative operators' settings

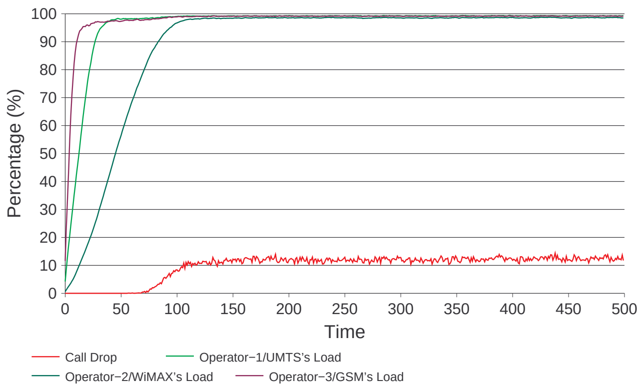


Figure 7.3: Fully Cooperative Scenario - Figure representing operators resource load and the aggregated call blocking percentage in fully cooperative operators' settings

cooperative approach in terms of resource utilization, call blocking and ultimately the revenue of operators (which is a function of utilization).

In order to investigate the performance of *user-centric network selection* gain of users in terms of their utility, we consider that users randomly generate requests of different audio, video and data specifying service preferred QoS i.e., excellent, good and fair. These requests are generated using poisson distribution with the mean $\bar{\mu}_{uc}$. To make this scenario comparable to network-centric scenario, the mean $\bar{\mu}_{uc}$ is kept as $\bar{\mu}_{uc} = \sum_{p=1}^{3} \bar{\mu}_p$, meaning thereby the same number of users' requests are generated in the coverage area as in network-centric case, but now users have no long-term contractual agreements with operator, and they are free to get associated with any operator. Operators' offer vary over time specially in terms of offered prices and offered QoS attribute values owing to the network condition, congestion and operator preferences. This results in triggering the interface selection decision. Performance of our auction-based interface selection approach is evaluated against the network-centric approach in terms of average values over user's throughput, delay, jitter, packet-loss and payed price over 500 simulation instances are depicted in Fig. 7.4. As can be seen that auction-based approach performs better by about 10% in user throughput and about 9% in the price. It should be noted that improvement in throughput is achieved at the cost of frequent handovers. Thus to address this issue, we implement the fuzzy based solution on the similar lines as discussed in Chapter 3.

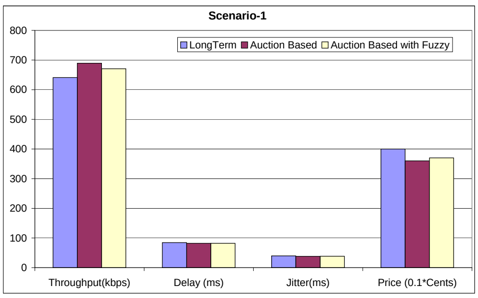


Figure 7.4: User gain in user-centric network selection - Figure representing the throughput, QoS and price comparisons of *long-term-based* approach against *auction-based* and *auction-based with fuzzy* approaches

The results reveal that in terms of both throughput and price, auction-based with fuzzy

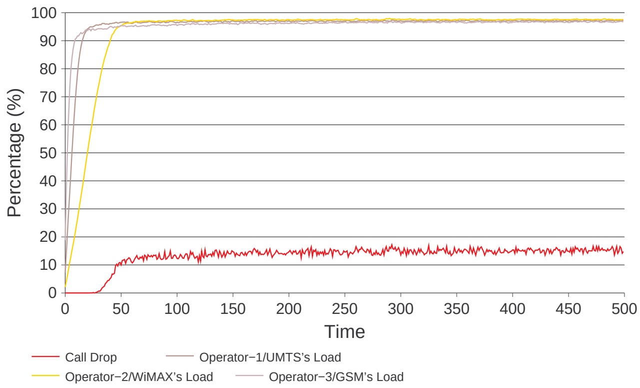


Figure 7.5: Operators' load and call blocking in user-centric network selection scenario - Figure representing the load of different operators and aggregated call drop percentage in user-centric network selection settings

approach performs almost the same as auction-based approach, but with almost half the amount of handovers.

We also compare auction based interface selection in terms of call blocking rate and resource utilization with our game-theoretic network-centric resource allocation. Fig. 7.5 reveals that user-centric approach performs better in terms of resource utilization, owing to the fact that users are always able to connect to any operator if blocked by one operator. Comparing the results in Fig. 7.5 with our game-theoretic approach in Fig. 7.3 it can be concluded that user-centric approach behaves somewhat similar to the cooperative game theoretic approach in terms of resource utilization and call blocking, and performs better than other network-centric approaches (please refer to Chapter 5 for the related comparison). This result dictates that auction-based user-centric and cooperative network-centric approaches provide similar incentives in terms of better resource utilization, less call blocking, and more satisfied users. Moreover, assuming that efficient resource utilization ultimately means higher revenues for the operators, these two approaches also increase operator satisfaction.

7.5 Conclusion

In this chapter, we compared the performance of proposed network-centric resource allocation approach against the user-centric network selection in terms of resource utilization and call blocking probability and user received throughput. The results indicate that user-centric network selection has a significant potential for satisfying both user and operators, thereby improving user experience and operators' resource utilization. Interestingly, user-centric results resemble those of the cooperative network-centric results. One may intuitively infer that these two approaches also result in higher revenues for operators when compared with other approaches discussed in the chapter.

Part III

Learning Games based Network Selection Category

This category introduces the concept of learning to the network selection problem discussed in the earlier chapters. We focus on investigating the game dynamics and learning schemes in network selection. In this category, we discuss the coalition formation at the user level using evolutionary game theoretic approach. We also highlight the open research issues, when it comes to the use of coalitional game theoretic approaches. This category is decomposed into following two chapters:

- **Chapter 8** *Learning in Network Selection* : In this chapter, we study game dynamics and learning schemes for network selection in heterogeneous wireless networks and introduce a novel learning scheme called *cost-to-learn*. We construct various heterogeneous combined fully distributed payoff and strategy reinforcement learning. We study the performance of the proposed learning approach by applying it to a user-centric wireless network scenario and user-centric IPTV service provider selection scenario.
- **Chapter 9** *Coalition Based User-Centric Network Selection* : In this chapter, we focus on the user coalition formation in the user centric paradigm, we present a novel approach of coalition network selection. We use evolutionary game-theoretic approach to model this problem. We also examine fully distributed algorithms for global optima in network selection games. Then, the problem of dynamic network formation and evolutionary coalitional games in network selection are investigated. The performance of the proposed approach is studied through simulations using OPNET modeller 15.0.

8

Learning in Network Selection

In this chapter, we study game dynamics and learning schemes for network selection in heterogeneous 4G networks. We introduce a novel learning scheme called cost-to-learn that incorporates the cost to switch, the switching delay, and the cost of changing to a new action (i.e., new network technology operator) and, captures the realistic behavior of the users that we have experimented on OPNET simulations. Considering a dynamic and uncertain environment where the users and operators have only a numerical value of their own payoffs as information, we construct various heterogeneous combined fully distributed payoff and strategy reinforcement learning: the users try to learn their own optimal payoff and their optimal strategy simultaneously. We prove the approximation to differential equations. Using evolutionary game dynamics, we prove the convergence and stability properties in specific classes of dynamic robust games. We provide various numerical examples and OPNET simulations in the context of network selection in WLAN and LTE.

8.1 Introduction

From the discussion over heterogeneous of telecom landscape and user centric network selection paradigm, one can conclude that such scenario is immensely dynamic. Since the basic assumption in user-centric network selection configuration says that users are capable of playing their best response(s) to the available service offers from the operators (where the user response is strictly driven by the user preferences). We now comment on the claim that user-centric network selection is dynamic. It is evident that operators in user-centric network selection paradigm adapt their offers from time to time to increase their payoffs, similarly wireless medium characteristics that impact the user perceived QoS e.g., delay, packet loss, jitter, etc. add much to strengthen the claim. Last but not the least comes the mobility of users, context change, and changing user preferences provide basic justification to claim that envisioned user-centric scenario is dynamic. Many approaches discussed in the literature review of Chapter 3 do not consider the dynamic of system. However, as the complexity of the existing system grows, and the environment cannot be assumed to be constant, we need to study and explore the dynamic behavior of such systems which involve not only the time dependencies and the state of the environment but also the variability of the demands, the uncertainty of the system parameters, the random activity of the users, the time delays, error and noise in the measurement over long-run interactions, etc.

In many dynamic interactions, one would like to have a learning and adaptive procedure that does not require any information about the other users' actions or payoffs and as little memory (small number of parameters in terms of past own-actions and past own-payoffs) as possible. Such a rule is said to be *uncoupled* or *fully distributed*. However, it has been shown in (175) that for a large class of games, no such general algorithm causes the users' period-by-period behavior to converge to Nash equilibrium (no user can improve its payoff by unilateral deviation). Hence, most of the time, there is no guarantee that the behaviors of fully distributed learning algorithms and dynamics will come close to Nash equilibrium. By introducing public signals (but irrelevant-payoff signals) into the interaction, each user (player) can choose her action according to her observation of the value of the signal. Then, a strategy assigns an action to every possible observation a user can make. If no user would want to deviate from the recommended strategy (assuming the others don't deviate), the distribution is called a correlated equilibrium. The works in (176), (177) showed that *regret-minimizing procedures* can cause the empirical frequency distribution of play to converge to the set of correlated equilibria. Note that the set of correlated equilibria is convex and includes the convex hull of the set of Nash equilibria. We make use of game theoretic approach to capture the dynamics of system and take decision of network selection. As detailed in Chapter 3 various game theoretic approach have been used to address the network selection issues e.g., (178),(75). However, many networking and communication games are subject to uncertainty (i.e., robust games).

Uncertainties may come from the measurements, the noisy observations, the computation errors or the incomplete information. In robust games with a large number of actions, users are inherently faced with limitations in both their observational and computational capabilities.

Accordingly, users in such games need to make their decisions using algorithms that accommodate limitations in information gathering and processing. This disqualifies some of the well known decision making models (such as *fictitious play*, best reply, gradient descent, model-based algorithms etc) in which each user must monitor the actions of every other user and must optimize over a high dimensional probability space (cartesian product of the action spaces). The authors in (179) proposed a modified version of the fictitious play called joint fictitious play with inertia and proved its convergence in potential games and network congestion games using the finite improvement path (FIP) property. Note that in the finite improvement path procedure only one user moves at a given time slot (simultaneous moves are not allowed). For this reason, the FIP is not adapted if the network does not follow a prescribed rule evolution with observation capabilities. One of the well-known learning schemes for simultaneous-move games is the *interactive trial and error learning*. In (180), it is shown that the interactive trial and error learning, implements Nash equilibrium behavior in any game with generic payoffs and which has at least one pure Nash equilibrium. The interactive trial and error learning is a completely uncoupled learning rule, such that, when used by all users in a game, period-by-period play comes close to pure Nash equilibrium play a high proportion of the time, provided that the game has such an equilibrium and the payoffs satisfy an interdependency condition. However, in games without pure Nash equilibrium (such as matching pennies, penalty games, many security games etc), the interactive trial and error learning does not implement Nash equilibria. Another point is that even if the trial-and-error process is at a pure Nash equilibrium, it can move from this point and the process restarts again.

Since we know from the *Nash theorem* that any finite game in strategic form has at least one equilibrium in mixed strategies and the same result can be applied to finite robust games under suitable condition on the mathematical expectation, it remains a question of algorithms (181) for computing one of them and the selection of the most efficient equilibrium (if any). In the line of mixed equilibria search (including pure equilibria), several stochastic learning procedures have been proposed. Strategy reinforcement learning and dynamics in finite games have been studied in (182, 183, 184, 185) for both pure and mixed equilibria. These works used stochastic approximation techniques (186, 187, 188) to derive ordinary differential equations (ODE) equivalent to the adjusted replicator dynamics (189). By studying the orbits of the replicator dynamics, one can gets some convergence/divergence and stability/instability properties of the system. However the replicator dynamics may not lead to *approximate equilibria* even in simple games. Convergence properties in a special class of games such as weakly acyclic games and best-response potential games can be found in (190). Recently, distributed learning algorithms and feedback based update rules have been extensively developed in networking and communication systems. Particular cases of Bush-Mosteller (191) with slight changes have been examined in (182, 184). The authors in (184) have studied stochastic learning algorithm in a distributed discrete power control problem. They proposed a n-person, nonzero sum power control game based on the energy efficiency function. In their model, each mobile user evaluates a power strategy by computing a payoff value. This evaluation is performed using a strategy-reinforcement learning introduced by Bush & Mosteller (1949-55, (191)). The Bush & Mosteller's reinforcement learning can be approximated by an ordinary differential equation by standard stochastic approximation theory. The Bush & Mosteller's stochastic reinforcement learning has been applied to vehicle suspension control in (192). The authors in (184) have investigated in detail the convergence and the divergence issues for the two-user two-action case. However, a payoff-reinforcement learning (Q-value learning) is not examined in their models. Closely related works on network selection and dynamics can be found in (193, 194, 195, 196). The authors in (194) focus on service provider selection, where users' service provider selection criteria encamps the subscription fee and coverage. Authors model the competition between operators using game theoretic approach and study the impact of user types distribution within the coverage area in fixed & dynamic configurations. The work in (193) model competition between incumbent and new entrant technologies. The paper discusses users' technology adaptation decisions and in this connection authors propose users' utility, which is defined on a very abstract level in the multi-technology settings. Authors also study the impact and equilibria for different values of involved attributes and configurations. In (195), authors model the switching between two networks namely Best Effort (BE) and Next Generation Network (NGN), where these two technologies can be regarded as the carrier platforms. Authors characterize NGN technology technically stronger than its counterpart in the model. The decision instances reside on either sides of the carrier platforms and hence creating two markets i.e., content providers market and users market. This study mainly focuses on investigating the equilibrium criteria in platform selection game for operators' choice of prices. Similarly (196) studies user subscription dynamics, revenue maximization, and equilibrium characteristics in two different markets (i.e., monopoly and duopoly). Although the research works (193, 194, 195, 196) discuss the co-existence of network technologies, however they do not discuss the technical realization of the technologies integration. We, on the other hand have provided and extensively implemented the technical solution i.e., IMS functional entities in the core network, integration of LTE & WLAN network technologies based on 3GPP standards, and IPv6 based mobility management, etc. The consequence of such extensive technical solution implementation is the increased confidence level in attained results specifically if the network selection model involves dynamic wireless parameters. It should be noted that in the referred research literature, user evaluation of the network selection is based on abstract functions i.e., not concretely taking the technical QoS indices into account. However, we use user utility function, that captures user satisfaction with respect to both technical and economic aspects. We also validate the proposed user satisfaction against the objective measurements for three different types of applications i.e., Voice over IP (VoIP), Video and File Transfer Protocol (FTP). It should be noted that the objective measurements were carried out in the extensively developed measurement setup following ITU-T and 3GPP standards. The concept of technology switchover costs is discussed in (194). However, in the first place, authors briefly comment on technology switching costs in their future work section, thus no such costs are involved in their service provider selection modeling, secondly the authors envision costs mainly as a monetary penalty and not as the technical costs. However, we claim that in network selection paradigm, such costs may realistically be translated into signalling costs, switching from broadband to narrowband codec, etc. Our implementation extensively takes care of codec switchover (for real time applications), network technology handover costs in the network selection decision.

In (197), authors examined distributed learning in multi-armed bandit with multiple players under based on a time-division fair sharing (TDFS) of the best arms. Note that time division like-technique is not possible in a distributed random environment since the players activity is random. Application of best-response adjustment to network security can found in (198). In (199) the authors propose a distributed mechanism for enforcing and learning the cooperation among the greedy nodes in packet forwarding.

The authors in (200) proposed Q-learning algorithms for non-zero-sum finite stochastic games in wireless networks. However a general convergence result of such algorithms remain a challenging open problem. We give a convergence result for such games with uncontrolled and ergodic state transitions. In (201), the authors analyzed the robustness of the dynamics when users join and leave the network. However, the case where the users have different behavior (different learning patterns and different speed of learning) is not examined in (201). As we will see in this chapter, these two parameters are very important in terms of convergence time of the combined learning in a dynamic unknown environment. Delayed evolutionary game dynamics have been studied in (202, 203) but in continuous time. The authors in (202, 203) have shown that an *evolutionary stable strategy* (which is robust to invasions by small fraction of users) can be unstable for large time delays and they provided sufficient conditions of stability of delayed Aloha-like systems.

Different from *distributed learning optimization*, we use the term *strategic learning* (204). By strategic learning, we mean how users are able to learn about the dynamic environment under their complex and interdependent strategies - the convergence of learning of each user depends on the others and so on.

Only few convergence results are known in strategic learning. These are obtained for a particular structure of the payoffs and action spaces:

•$[R1]$ Lyapunov expected games (any finite robust game in which the expected payoff leads to an hybrid dynamics which has a Lyapunov function). Particular classes of these games are potential games, common interest games, dummy games, congestion games etc under specific dynamics.

•$[R2]$ Two-user-two-action games for well-chosen learning patterns and generic payoffs,

•$[R3]$ Particular class of games with monotone expected payoffs,

•$[R4]$ Particular classes of supermodular games, submodular games in low dimension (2 or 3),

•$[R5]$ Dominant solvable games (games with a dominant strategy).

Detailed analysis of these results can be found in (205, 206, 207, 208).

All the above convergence results [R1-R5] for specific classes of games can be extended into the class of robust games.

Once we move from these specific classes of games, the convergence of learning schemes must be proven. Cases of non-convergence under homogeneous learning including *cycling games* which leads to limit cycles and oscillating behaviors may occur. Using specific learning rates and by carefully choosing the learning scheme, the multiple-scale learning is known to be convergent in specific classes of games that generalize Shapley's games, Jordan games, matching pennies, variations of Rock-Scissor-Paper games, etc. The generalization uses the Dulac's theorem and Poincaré - Bendixson theorem (see (209)) which states that for planar systems if the w-limit set is non-empty and if the trace of the Jacobian of the system (the divergence) is of constant sign for all pair of the variables, then the system is convergent. Note that these results are limited to planar systems i.e they can be used only for two-action games or at most three-actions symmetric games.

Using the multiple time-scale stochastic approximations developed in (210, 211, 212, 213), we study various combined learning algorithms for stochastic games with particular state transition structures.

8.1.1 Case of Interests of this Chapter

In this chapter, we focus on hybrid and combined strategic learning for general-sum stochastic dynamic games with incomplete information and action-independent state transition with the following novelties:

- In contrast to the standard learning approaches widely studied in the literature (177, 180, 182, 190) where the users follow the same predetermined scheme, here we relax this assumption and the users do not need to follow the same learning patterns. We propose different learning schemes that the users can adopt. This leads to *heterogeneous learning*. Our motivation for heterogeneous learning follows from the observation that, in heterogeneous wireless systems, the users may not see the environment in the same way, they may have different capabilities and different adaptation degrees. Thus, it is important to take into consideration these differences when analyzing the behavior of the wireless system. *As we will see the heterogeneity in the learning is crucial in term of convergence of certain systems.*

- Each user does not need to update her strategy at each iteration. The updating times are random and unknown by the users. Usually, in the iterative learning schemes the time slots during which the user updates are fixed. Here we do not restrict to fixed updating time. This is because some users come in or exit temporarily, and it may be costly to update or for some other reasons, the users may prefer to update their strategies at another time. One may think that if some of the user does not update often, the strategic learning process will be slower in terms of convergence time; this statement is less clear because the off-line users may indirectly help the online users to converge and, when they wake-up they respond to an already converged system, and so on.

- Each user can be in active mode or in sleep mode. When a user is active, she can select from a set of learning patterns to update her strategies and/or estimations. The users can change their learning pattern during the interaction. This leads to an *hybrid learning*.

- We propose a *cost of learning* CODIPAS-RL which takes into consideration the cost of moves from one action to another one. In the context of operator / technology selection, the cost of learning is very important, it can represent the delay needed to change a technology or a production or a upgrade cost.

- We establish a connection between the asymptotic pseudo-trajectory of the learning schemes to the *hybrid evolutionary game dynamics* developed in (214).

- In contrast to the standard learning frameworks developed in the literature which are limited to a finite and fixed number of users, we extend our methodology to large systems with multiple classes of populations. This allows us to address the "curse of dimensionality" problems when the size of the interacting system is very large. Finally, different *mean field learning* are proposed using *Fokker-Planck-Kolmogorov* equations. The case of noisy and time delayed payoffs is also discussed.

- Our theoretical findings are illustrated numerically in heterogeneous wireless networks with multiple classes of users and multiple technologies: wireless local area networks (WLAN) and long term evolution (LTE) using Mathematica and OPNET Simulation.

To the best of the authors' knowledge, this work may be counted amongst the first ones analyzing (i) the cost of learning in an heterogeneous and unknown environment (ii) convergence results for hybrid learning schemes, (iii) mean field learning in games subject to uncertainty and their connection to evolutionary game dynamics, (iv) combining theoretical results with the experimental learning scenarios using OPNET simulator.

We summarize some of the notations and their description in Table 8.1.

8.2 The Setting

8.2.1 Description of the Dynamic Environment

We examine a system with a finite number of *potential users*. The set of users is denoted by $\mathcal{N} = \{1, 2, \ldots, n\},\ n = |\mathcal{N}|$. The number n can be 10, 10^4 or 10^6. Each user has a finite number of actions denoted by $\mathcal{A}_j$ (which can be arbitrary large). Time is discrete and the space of time is $\mathbb{N} = \{0, 1, 2, \ldots\}$. A user does not necessarily interact at all the time steps. Each user can be in one of the two modes: *active mode* or *sleep mode*. The set of users interacting at the current time is the set of active users $\mathcal{B}^n(t) \subseteq \mathcal{N}$. This time-varying set is unknown to the users.

Table 8.1: Summary of Notations

Symbol	Meaning
$\mathbb{R}^k$	$k-$dimensional Euclidean space
$\mathcal{W} \subseteq \mathbb{R}^k$	state space
$\mathcal{N}$	set of potential users (finite or infinite)
$\mathcal{B}^n(t)$	random set of active users at time t.
$\mathcal{A}_j$	set of actions of user j
$s_j \in \mathcal{A}_j$	a generic element of $\mathcal{A}_j$
$\mathcal{X}_j := \Delta(\mathcal{A}_j)$	set of probability distributions over $\mathcal{A}_j$
$a_{j,t} \in \mathcal{A}_j$	action of the user j at time t
$\mathbf{x}_{j,t} \in \mathcal{X}_j$	strategy of the user j at t
$u_{j,t}$	perceived payoff by user j at t
$\hat{\mathbf{u}}_{j,t} \in \mathbb{R}^{\lvert\mathcal{A}_j\rvert}$	estimated payoff vector of user j at t
l^2	space of sequences $\{\lambda_t\}_{t\geq 0}$, $\sum_{t\in\mathbb{N}} \lvert\lambda_t\rvert^2 < +\infty$
l^1	space of sequences $\{\lambda_t\}_{t\geq 0}$, $\sum_{t\in\mathbb{N}} \lvert\lambda_t\rvert < +\infty$
$(\lambda_{j,t}, \nu_{j,t})$	learning rates of user j at t
$m_t^p(.)$	Mean field limit at time t

When a user is in active mode, he/she does an experiment, and gets a measurement or a reaction to his decision, denoted $u_{j,t} \in \mathbb{R}$ (this may be delayed as we will see). Let $\mathcal{X}_j := \Delta(\mathcal{A}_j)$ be the set of probability distributions over $\mathcal{A}_j$ i.e the simplex of $\mathbb{R}^{|\mathcal{A}_j|}$. The number $u_{j,t} \in \mathbb{R}$ is the realization of a random variable $\tilde{U}_{j,t}$ which depends on the state of nature $\mathbf{w}_t \in \mathcal{W}$ and the action of the users where the set $\mathcal{W}$ is a subset of a finite dimensional Euclidean space. Each *active user* j updates her/his current strategy $\mathbf{x}_{j,t+1} \in \Delta(\mathcal{A}_j)$ based on his experiment and its prediction for his future interaction via the payoff estimation $\hat{\mathbf{u}}_{j,t+1} \in \mathbb{R}^{|\mathcal{A}_j|}$.

This leads into the class of dynamic games with unknown payoff function and with imperfect monitoring (the last decisions of the other users are not observed). A payoff in the long-run interaction is the average payoff which we assume to have a limit. In that case, under the stationary strategies, the limiting of the average payoff can be expressed as an expected game i.e the game with payoff $v_j : \prod_{j'\in\mathcal{N}} \mathcal{X}_{j'} \longrightarrow \mathbb{R}$, $v_j(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n) = \mathbb{E}_{\mathbf{x}_1,\mathbf{x}_2,\ldots,\mathbf{x}_n}\left(\mathbb{E}\tilde{U}_j\right)$

Assumptions on user's information: The only information assumed is that each user is able to observe or to measure a noisy value of its payoff when she/he is active and update its strategy based on this measurement.

Note that the users do not need to know their own action space in advance. Each user can learn his action space (using for example exploration techniques). In that case, we need to add an exploration phase or a progressive exploration during the dynamic game. The result is that if the all the actions have been *explored* and sufficiently *exploited* and if the learning rate are well-chosen then the prediction can be "good" enough.

Next, we describe how the dynamic robust game evolves.

8.2.2 Description of the Dynamic Game

The dynamic robust game is described as follows:

- At time slot $t = 0$, $\mathcal{B}^n(0)$ is the set of active users. The set $\mathcal{B}^n(0)$ is not known by the users. We assume that each user has its internal state in $\{0, 1\}$. The number 1 corresponds to the case where $j \in \mathcal{B}^n(0)$, and 0 otherwise. Each user $j \in \mathcal{B}^n(0)$ chooses an action $a_{j,0} \in \mathcal{A}_j$. The set $\mathcal{A}_j$ is not assumed to be known in advance by user j, we assume that he can explore progressively during the interactions. He measures a numerical noisy value of its payoff which corresponds to a realization of the random variables depending on the actions of the other users and the state of the nature, etc. He initializes its estimation to $\hat{\mathbf{u}}_{j,0}$. The non-active users get zero.

- At time slot t, each user $j \in \mathcal{B}^n(t)$ has an estimation of his payoffs, chooses an action based its own-experiences and experiments a new strategy. Each user j measures/observes an output $u_{j,t} \in \mathbb{R}$, (eventually after some time delay). Based on this target $u_{j,t}$, the user j updates its estimation vector $\hat{\mathbf{u}}_{j,t} \in \mathbb{R}^{|\mathcal{A}_j|}$ and built a strategy $\mathbf{x}_{j,t+1} \in \mathcal{X}_j$ for his next interaction. The strategy at $t + 1$, $\mathbf{x}_{j,t+1}$ is a function only of $\mathbf{x}_{j,t}, \hat{\mathbf{u}}_{j,t}$ and the most recent target value. Since the users do not interact always, each user has its own clock which counts the activity of that user. At time step t, the clock of user j is $\theta_j(t) = \sum_{t' \leq t} \mathbb{1}_{\{j \in \mathcal{B}^n(t')\}}$. We assume $\liminf_{t \longrightarrow \infty} \ \theta_j(t)/t > 0$.

  Note that the exact value of the state of the nature at time t and the previous strategies $\mathbf{x}_{-j,t-1} := (\mathbf{x}_{k,t-1})_{k \neq j}$ of the other users and their past payoffs $\mathbf{u}_{-j,t-1} := (u_{k,t-1})_{k \neq j}$ are unknown to user j at time t.

- The game moves to $t + 1$.

In addition, we extend the framework to the delayed payoff measurement case. This means that, the perceived payoffs at time t are not the instantaneous payoff but the noisy value of the payoff at $t-\tau_j$ i.e $u_{j,t-\tau_j}$.

In order to define rigourously the dynamic robust game, we need some preliminaries. Next, we introduce the notions of histories, strategies and payoffs (performance metrics). The payoff is associated to a (behavioral) strategy profile which is a collection of mapping from the set of histories to the available actions at the current time.

Histories A user's information consists of his (own) past activities, own-actions and measured own-payoffs. A private history up to t for user j is a collection

$$h_{j,t} = (b_{j,0}, a_{j,0}, u_{j,0}, b_{j,1}, a_{j,1}, u_{j,1}, \ldots, b_{j,t-1}, a_{j,t-1}, u_{j,t-1})$$

in the set $H_{j,t} := (\{0,1\} \times \mathcal{A}_j \times \mathbb{R})^t$. where $b_{j,t} = \mathbb{1}_{\{j \in \mathcal{B}^n(t)\}}$ which is 1 if j is active at time t and 0 otherwise.

Behavioral Strategy A behavioral strategy for user j is a mapping $\tilde{\tau}_j : \bigcup_{t\geq 0} H_{j,t} \longrightarrow \mathcal{X}_j$. We denote by Σ_j the set of behavioral strategies of user j.

The set of complete histories of the dynamic robust game after t stages is $H_t = (2^{\mathcal{N}} \times \mathcal{W} \times \prod_{j\in\mathcal{N}} \mathcal{A}_j \ \times \mathbb{R}^n)^t$, it describes the set of active users, the states, the chosen actions and the received payoffs for all the users at all past stages before t. The set $2^{\mathcal{N}}$ denotes the set of all the subsets of $\mathcal{N}$ (except the empty set). A behavioral strategy profile $\tilde{\tau} = (\tilde{\tau}_j)_{j\in\mathcal{N}} \in \prod_j \Sigma_j$ and a initial state $\mathbf{w}$ induce a probability distribution $P_{\mathbf{w},\tilde{\tau}}$ on the set of plays $H_\infty = (\mathcal{W} \times \prod_j \mathcal{A}_j \ \times \mathbb{R}^n)^{\mathbb{N}}$.

Payoffs Assume that $\mathbf{w}, \mathcal{B}^n$ are independent and independent of the strategy profiles. For a given $\mathbf{w}, \mathcal{B}^n$, we denote

$$U_j^{\mathcal{B}^n}(\mathbf{w}, \mathbf{x}) := \mathbb{E}_{(\mathbf{x}_k)_{k\in\mathcal{B}^n}} \tilde{U}_j^{\mathcal{B}^n}(\mathbf{w}, (a_k)_{k\in\mathcal{B}^n}).$$

Let $\mathbb{E}_{\mathbf{w},\mathcal{B}^n}$ be the mathematical expectation relatively to the measure generated by the random variables $\mathbf{w}, \mathcal{B}^n$. Then, the expected payoff can be written as $\mathbb{E}_{\mathbf{w},\mathcal{B}^n} \tilde{U}_j^{\mathcal{B}^n}(.,.)$.

We focus on the limiting of the average payoff i.e $F_{j,T} = \frac{1}{T}\sum_{t=1}^T u_{j,t}$. The long-term payoff reduces to

$$\frac{1}{\sum_{t=1}^T \mathbb{1}_{\{j\in\mathcal{B}^n(t)\}}} \sum_{t=1}^T u_{j,t} \mathbb{1}_{\{j\in\mathcal{B}^n(t)\}},$$

when considering only the activity of user j. We assume that we do not have short-term users or equivalently the probability for a user j to be active is strictly positive. Given a initial state $\mathbf{w}$

and a strategy profile $\tilde{\tau}$, the payoff of user j is the superior limiting of the Cesaro-mean payoff $\mathbb{E}_{\mathbf{w},\tilde{\tau},\mathcal{B}^n} F_{j,T}$. We assume that $\mathbb{E}_{\mathbf{w},\tilde{\tau},\mathcal{B}^n} F_{j,T}$ has a limit. Then, the expected payoff of an active user j is denoted by $v_j(e_{s_j}, \mathbf{x}_{-j}) = \mathbb{E}_{\mathbf{w},\mathcal{B}^n} U_j^{\mathcal{B}^n}(\mathbf{w}, e_{s_j}, \mathbf{x}_{-j})$ where e_{s_j} is the vector unit with 1 at the position of s_j and zero otherwise.

Definition 10 (Expected robust game)**.** *We define the expected robust game as* $\left(\mathcal{N}, (\mathcal{X}_j)_{j\in\mathcal{N}}, \mathbb{E}_{\mathbf{w},\mathcal{B}^n} U_j^{\mathcal{B}^n}(\mathbf{w}, .)\right)$

Definition 11. *A strategy profile* $(\mathbf{x}_j)_{j\in\mathcal{N}} \in \prod_{j=1}^n \mathcal{X}_j$ *is a (mixed) state-independent equilibrium for the expected robust game if and only if* $\forall j \in \mathcal{N},\ \forall \mathbf{y}_j \in \mathcal{X}_j$,

$$\mathbb{E}_{\mathbf{w},\mathcal{B}^n} U_j^{\mathcal{B}^n}(\mathbf{w}, \mathbf{y}_j, \mathbf{x}_{-j}) \leq \mathbb{E}_{\mathbf{w},\mathcal{B}^n} U_j^{\mathcal{B}^n}(\mathbf{w}, \mathbf{x}_j, \mathbf{x}_{-j}), \tag{8.1}$$

The existence of solution of Equation (8.1) is equivalent to the existence of solution of the following *variational inequality problem*: find $\mathbf{x}$ such that

$$\langle \mathbf{x} - \mathbf{y}, V(\mathbf{x}) \rangle \geq 0,\ \forall \mathbf{y} \in \prod_j \mathcal{X}_j$$

where $\langle ., . \rangle$ is the inner product, $V(\mathbf{x}) = [V_1(\mathbf{x}), \ldots, V_n(\mathbf{x})]$,

$$V_j(\mathbf{x}) = [\mathbb{E}_{\mathbf{w},\mathcal{B}} U_j^{\mathcal{B}}(\mathbf{w}, e_{s_j}, \mathbf{x}_{-j})]_{s_j \in \mathcal{A}_j}.$$

Remark 15. *Note that an equilibrium of the expected robust game may not be an equilibrium (of the robust game) at each time slot. This is because* $\mathbf{x}$ *is an equilibrium for expected robust game does not imply that* $\mathbf{x}$ *is an equilibrium of the game* $\mathcal{G}(\mathbf{w})$ *for some state* $\mathbf{w}$ *and the set of active users may vary.*

Lemma 5. *Assume that* $\mathcal{W}$ *is compact. Then, The expected robust game with unknown state and variable number of interacting users has at least one (state-independent) equilibrium.*

The existence of such equilibrium points is guaranteed since the mappings $v_j : (\mathbf{x}_j, \mathbf{x}_{-j}) \longmapsto \mathbb{E}_{\mathbf{w},\mathcal{B}} U_j^{\mathcal{B}}(\mathbf{w}, \mathbf{x}_j, \mathbf{x}_{-j})$ is jointly continuous, quasi-concave in $\mathbf{x}_j$, the spaces $\mathcal{X}_j$, are non-empty, convex and compact. Then, the result follows by using Kakutani fixed point theorem or by applying Nash theorem to the expected robust game.

Since we have existence of state-independent equilibrium under suitable conditions, we seek for heterogeneous and combined algorithms to locate the equilibria.

8.3 CODIPAS-RL

We propose an hybrid, delayed, COmbined fully DIstributed PAyoff and Strategy Reinforcement Learning in the following form: (hybrid-delayed-CODIPAS-RL)

$$\begin{cases} \mathbf{x}_{j,t+1}(s_j) - \mathbf{x}_{j,t}(s_j) = \\ 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} \sum_{l\in\mathcal{L}} 1\!\!1_{\{l_{j,t}=l\}} K^{1,(l)}_{j,s_j}(\lambda_{j,\theta_j(t)}, a_{j,t}, u_{j,t-\tau_j}, \hat{\mathbf{u}}_{j,t}, \mathbf{x}_{j,t}), \\ \hat{\mathbf{u}}_{j,t+1}(s_j) - \hat{\mathbf{u}}_{j,t}(s_j) = \\ 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} K^2_{j,s_j}(\nu_{j,\theta_j(t)}, a_{j,t}, u_{j,t-\tau_j}, \hat{\mathbf{u}}_{j,t}, \mathbf{x}_{j,t}), \\ j\in\mathcal{N}, t\geq 0, a_{j,t}\in\mathcal{A}_j, s_j\in\mathcal{A}_j, \\ \theta_j(t+1) = \theta_j(t) + 1\!\!1_{\{j\in\mathcal{B}^n(t)\}}, \\ t\geq 0,\ \mathcal{B}^n(t)\subseteq\mathcal{N}, \\ \mathbf{x}_{j,0}\in\mathcal{X}_j, \hat{\mathbf{u}}_{j,0}\in\mathbb{R}^{|\mathcal{A}_j|}. \end{cases}$$

where $\hat{\mathbf{u}}_{j,t} = (\hat{u}_{j,t}(s_j))_{s_j\in\mathcal{A}_j} \in \mathbb{R}^{|\mathcal{A}_j|}$ is a vector payoff estimation of user j at time t. Note that when user j uses $a_{j,t} = s_j$, he observes only his measurement corresponding to that action but not those of the other actions $s'_j \neq s_j$. Hence he needs to estimate/predict them via the vector $\hat{\mathbf{u}}_{j,t+1}$. The functions K^1 and λ are based on estimated payoffs and perceived measured payoff (delayed and noisy) such that the invariance of simplex is preserved almost surely. The function K^1_j defines the strategy learning pattern of user j and $\lambda_{j,\theta_j(t)}$ is its strategy learning rate. If at least two of the functions K_j are different then we refer to *heterogeneous learning* in the sense that the learning schemes of the users are different. If all the K^1_j are identical but the learning rates λ_j are different, we refer to *learning with different speed*: slow learners, medium or fast learners. Note that the term $\lambda_{j,\theta_j(t)}$ is used instead of $\lambda_{j,t}$ because the global clock $[t]$ is not known by user j (he knows only how many times he has been active, the activity of others is not known by j). $\theta_j(t)$ is a random variable that determines the local clock of j. Thus, the updates are asynchronous. The functions K^2_j, and ν_j are well-chosen in order to have a good estimation of the payoffs. τ_j is a time delay associated to user j in its payoff measurement. The payoff $u_{j,t-\tau_j}$ at $t-\tau_j$ is perceived at time t. We examine the case where the users can choose different CODIPAS-RL patterns during the dynamic game. They can select among a set of CODIPAS-RLs denoted by $\mathcal{L}_1,\ldots,\mathcal{L}_m, m\geq 1$. The resulting learning scheme is called *hybrid CODIPAS-RL*. The term $l_{j,t}$ is the CODIPAS-RL pattern chosen by user j at time t.

8.3.1 CODIPAS-RL patterns

We examine the above dynamic game in which each user learns according to a specific CODIPAS-RL scheme.

8.3.1.1 Bush-Mosteller based CODIPAS-RL: $\mathcal{L}_1$

The learning pattern $\mathcal{L}_1$ is given by

$$x_{j,t+1}(s_j) - x_{j,t}(s_j) = \lambda_{\theta_j(t)} \mathbb{1}_{\{j\in\mathcal{B}^n(t)\}} \times$$

$$\frac{u_{j,t} - \Gamma_j}{\sup_{\mathbf{a},w} |U_j(w,a) - \Gamma_j|} \left(\mathbb{1}_{\{a_{j,t}=s_j\}} - \mathbf{x}_{j,t}(s_j) \right), \tag{8.2}$$

$$\hat{u}_{j,t+1}(s_j) - \hat{u}_{j,t}(s_j) =$$

$$\nu_{\theta_j(t)} \mathbb{1}_{\{a_{j,t}=s_j, j\in\mathcal{B}^n(t)\}} \left(u_{j,t} - \hat{u}_{j,t}(s_j)\right) \tag{8.3}$$

$$\theta_j(t+1) = \theta_j(t) + \mathbb{1}_{\{j\in\mathcal{B}^n(t)\}} \tag{8.4}$$

where Γ_j is a reference level of j. The first equation of $\mathcal{L}_1$ is widely studied in machine learning and have been initially proposed by Bush & Mosteller in 1949-55 (191). The second equation of $\mathcal{L}_1$ is a payoff estimation for the experimented action by the users. Combined together one gets a specific combined fully distributed payoff and strategy reinforcement learning based on Bush-Mosteller reinforcement learning.

8.3.1.2 Boltzmann-Gibbs based CODIPAS-RL: $\mathcal{L}_2$

$$x_{j,t+1}(s_j) - x_{j,t}(s_j) = \lambda_{\theta_j(t)} \mathbb{1}_{\{j\in\mathcal{B}^n(t)\}} \times$$

$$\left(\frac{e^{\frac{1}{\epsilon_j}\hat{\mathbf{u}}_{j,t}(s_j)}}{\sum_{s'_j\in\mathcal{A}_j} e^{\frac{1}{\epsilon_j}\hat{\mathbf{u}}_{j,t}(s'_j)}} - x_{j,t}(s_j) \right), \tag{8.5}$$

$$\hat{u}_{j,t+1}(s_j) - \hat{u}_{j,t}(s_j) =$$

$$\nu_{\theta_j(t)} \mathbb{1}_{\{a_{j,t}=s_j, j\in\mathcal{B}^n(t)\}} \left(u_{j,t} - \hat{u}_{j,t}(s_j)\right) \tag{8.6}$$

$$\theta_j(t+1) = \theta_j(t) + \mathbb{1}_{\{j\in\mathcal{B}^n(t)\}} \tag{8.7}$$

The strategy learning (8.5) of $\mathcal{L}_2$ is a Boltzmann-Gibbs based reinforcement learning. Note that the Boltzmann-Gibbs distribution can be obtained from the maximization of the perturbed payoff $U_j + \epsilon_j H_j$ where H_j is the entropy function i.e $H_j(\mathbf{x}_j) = -\sum_{s_j\in\mathcal{A}_j} x_j(s_j)\ln x_j(s_j)$. It is a smooth best response function. Here the Boltzmann-Gibbs mapping is based on the payoff estimation (the exact payoff vector is not known, only one component of a noisy value is observed). We denote the Boltzmann-Gibbs strategy by

$$\tilde{\beta}_{j,\epsilon_j}(\hat{u}_{j,t})(s_j) = \frac{e^{\frac{1}{\epsilon_j}\hat{\mathbf{u}}_{j,t}(s_j)}}{\sum_{s'_j\in\mathcal{A}_j} e^{\frac{1}{\epsilon_j}\hat{\mathbf{u}}_{j,t}(s'_j)}}$$

and the smooth best response to $\mathbf{x}_{-j,t}$ (also called Logit rule, Gibbs sampling or Glauber dynamics) is given by

$$\beta_{j,\epsilon_j}(\mathbf{x}_{-j,t})(s_j) = \frac{e^{\frac{1}{\epsilon_j}v_j(\mathbf{e}_{s_j},\mathbf{x}_{-j,t})}}{\sum_{s'_j\in\mathcal{A}_j} e^{\frac{1}{\epsilon_j}v_j(\mathbf{e}_{s'_j},\mathbf{x}_{-j,t})}}.$$

8.3.1.3 Imitative BG CODIPAS-RL: $\mathcal{L}_3$

$$x_{j,t+1}(s_j) - x_{j,t}(s_j) = \lambda_{\theta_j(t)} 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} x_{j,t}(s_j) \times \left(\frac{e^{\frac{1}{\epsilon_j}\hat{\mathbf{u}}_{j,t}(s_j)}}{\sum_{s'_j\in\mathcal{A}_j} x_{j,t}(s'_j) e^{\frac{1}{\epsilon_j}\hat{\mathbf{u}}_{j,t}(s'_j)}} - 1\right), \tag{8.8}$$

$$\hat{u}_{j,t+1}(s_j) - \hat{u}_{j,t}(s_j) = \nu_{\theta_j(t)} 1\!\!1_{\{a_{j,t}=s_j, j\in\mathcal{B}^n(t)\}} \left(u_{j,t} - \hat{u}_{j,t}(s_j)\right) \tag{8.9}$$

$$\theta_j(t+1) = \theta_j(t) + 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} \tag{8.10}$$

The strategy learning (8.8) of $\mathcal{L}_3$ is an imitative Boltzmann-Gibbs based reinforcement learning. The imitation here consists to play an action with a probability proportional to the previous uses of that action. The imitation learning leads to an *imitative evolutionary game dynamics*.

8.3.1.4 Multiplicative Weighted Imitative CODIPAS-RL: $\mathcal{L}_4$

$$x_{j,t+1}(s_j) - x_{j,t}(s_j) = 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} x_{j,t}(s_j) \times \left(\frac{(1+\lambda_{\theta_j(t)})^{\hat{\mathbf{u}}_{j,t}(s_j)}}{\sum_{s'_j\in\mathcal{A}_j} x_{j,t}(s'_j)(1+\lambda_{\theta_j(t)})^{\hat{\mathbf{u}}_{j,t}(s'_j)}} - 1\right), \tag{8.11}$$

$$\hat{u}_{j,t+1}(s_j) - \hat{u}_{j,t}(s_j) = \nu_{\theta_j(t)} 1\!\!1_{\{a_{j,t}=s_j, j\in\mathcal{B}^n(t)\}} \left(u_{j,t} - \hat{u}_{j,t}(s_j)\right) \tag{8.12}$$

$$\theta_j(t+1) = \theta_j(t) + 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} \tag{8.13}$$

The strategy learning (8.11) of $\mathcal{L}_4$ is a learning rate weighted imitative reinforcement learning. The main difference with $\mathcal{L}_2$ and $\mathcal{L}_3$ is that there is no parameter ϵ_j. The interior outcomes are necessarily exact equilibria of the expected (not approximated equilibria as in $\mathcal{L}_2$). It easy to show that (205) this leads to replicator dynamics (thus its interior stationary points are Nash equilibria).

8.3.1.5 Weakened Fictitious Play based CODIAPS-RL: $\mathcal{L}_5$

$$x_{j,t+1}(s_j) - x_{j,t}(s_j) \in \mathbb{1}_{\{i \in \mathcal{B}^n(t)\}} \times \left((1-\epsilon_t)\delta_{\arg\max_{s'_j} \hat{u}_{j,t}(s'_j)} + \epsilon_t \frac{\mathbb{1}}{|\mathcal{A}_j|} - x_{j,t}(s_j) \right), \tag{8.14}$$

$$\hat{u}_{j,t+1}(s_j) - \hat{u}_{j,t}(s_j) = \nu_{\theta_j(t)} \mathbb{1}_{\{a_{j,t}=s_j, j \in \mathcal{B}^n(t)\}} \left(u_{j,t} - \hat{u}_{j,t}(s_j)\right) \tag{8.15}$$

$$\theta_j(t+1) = \theta_j(t) + \mathbb{1}_{\{j \in \mathcal{B}^n(t)\}} \tag{8.16}$$

The last learning pattern $\mathcal{L}_5$ is a combined learning based on the weakened fictitious play (179, 215, 216). Here a user does not observe the action played by the other at the previous step and the payoff function is not known. Each user estimates its payoff function via the equations (8.15). The equation (8.14) consists to play one of the action with the best estimation $\hat{u}_{j,t}$ with probability $(1-\epsilon_t)$ and plays an arbitrary action with probability ϵ_t.

8.3.1.6 Payoff Learning

We mention some payoff learning based the idea of CODIPAS-RL: • $\mathcal{PL}_1$ **No-regret based CODIPAS-RL**

$$x_{j,t+1}(s_j) - x_{j,t}(s_j) = \mathbb{1}_{\{j \in \mathcal{B}^n(t)\}} R_t(s_j), \tag{8.17}$$

$$\hat{u}_{j,t+1}(s_j) - \hat{u}_{j,t}(s_j) = \nu_{\theta_j(t)} \mathbb{1}_{\{a_{j,t}=s_j, j \in \mathcal{B}^n(t)\}} \left(u_{j,t} - \hat{u}_{j,t}(s_j)\right) \tag{8.18}$$

$$\theta_j(t+1) = \theta_j(t) + \mathbb{1}_{\{j \in \mathcal{B}^n(t)\}} \tag{8.19}$$

$$R_t(s_j) = \frac{\phi([\hat{u}_{j,t}(s_j) - u_{j,t}]_+)}{\sum_{s'_j} \phi([\hat{u}_{j,t}(s'_j) - u_{j,t}]_+)} \tag{8.20}$$

The frequency of plays of strategy learning based on non-regret rule is known to be convergent to the set of correlated equilibria (175). Here the non-regret is based on the estimations.

• $\mathcal{PL}_2$: **Imitative No-regret based CODIPAS-RL**

$$x_{j,t+1}(s_j) - x_{j,t}(s_j) = \lambda_{\theta_j(t)} 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} \left(IR_t(s_j) - x_{j,t}(s_j)\right), \tag{8.21}$$

$$\hat{u}_{j,t+1}(s_j) - \hat{u}_{j,t}(s_j) =$$

$$\nu_{\theta_j(t)} 1\!\!1_{\{a_{j,t}=s_j, j\in\mathcal{B}^n(t)\}} \left(u_{j,t} - \hat{u}_{j,t}(s_j)\right) \tag{8.22}$$

$$\theta_j(t+1) = \theta_j(t) + 1\!\!1_{\{j\in\mathcal{B}^n(t)\}} \tag{8.23}$$

$$IR_t(s_j) = \frac{x_{j,t}(s_j)\phi([\hat{u}_{j,t}(s_j) - u_{j,t}]_+)}{\sum_{s'_j} x_{j,t}(s'_j)\phi([\hat{u}_{j,t}(s'_j) - u_{j,t}]_+)} \tag{8.24}$$

8.3.2 Main Results

We introduce the following assumptions. $[H2],\ \forall j \in \mathcal{N},\ \liminf_{t\longrightarrow\infty} \frac{\theta_j(t)}{t} > 0$

$[H3]$ $\lambda_t \geq 0,\ \lambda \in l^2\backslash l^1,\ \mathbb{E}\left(M_{j,t+1} \mid \mathcal{F}_t\right) = 0,\ \forall j,\ \mathbb{E}\left(\| M_{j,t+1} \|^2\right) \leq c_1 \left[1 + \sup_{t'\leq t} \| \mathbf{x}_{t'} \|^2\right]$ where $c_1 > 0$ is a constant.

It is important to mention that these assumptions H2-H3 are standard assumptions in stochastic approximations for almost sure convergence. However the vanishing learning rate can be time-consuming. In order to design fast convergent learning algorithms, *constant* learning rate ($\lambda_t = \lambda$) can be used as well, and convergence in law can be proved under suitable conditions. In this case the expectation of the gap between the solution of differential equations and the stochastic process is in order of the constant learning rate i.e $O(\lambda)$. In particular, if $\lambda \longrightarrow 0$ one has a weak convergence. Below the give the main results for time-varying learning rate under H2-H3.

Theorem 1 (proportional rates). *Suppose H2-H3 and consider proportional learning rates (the ratio is relatively similar and non-vanishing). Then, The asymptotic pseudo-trajectory of the hybrid-delayed-CODIPAS-RL is given by*

$$\left\{\begin{array}{c} \frac{d}{dt}\mathbf{x}_{j,t}(s_j) = g_{j,t} \sum_{l\in\mathcal{L}} p_{j,t,l} f^{(l)}_{j,s_j}(\mathbf{x}_{j,t}, \hat{\mathbf{u}}_{j,t}), \\ \frac{d}{dt}\hat{\mathbf{u}}_{j,t}(s_j) = \bar{g}_{j,t} \left(\mathbb{E}_{\mathbf{w},\mathbb{B}^n} U_j^{\mathcal{B}^n}(\mathbf{w}, \mathbf{e}_{j,s_j}, \mathbf{x}_{-j,t} - \hat{\mathbf{u}}_{j,t}(s_j))\right) \\ t \geq 0 \\ \mathbf{x}_{j,0} \in \mathcal{X}_j, \hat{\mathbf{u}}_{j,0} \in \mathbb{R}^{|\mathcal{A}_j|}. \end{array}\right.$$

where $g_{j,t}$ is the limiting of the expected value of $\frac{\lambda_{j,t}}{\max_{j'\in\mathcal{B}^n(t)} \max(\lambda_{j',t},\mu_{j',t})} 1\!\!1_{j\in\mathcal{B}^n(t)}$. The function $\bar{g}_{j,t}$ is the limiting of the expected value of $\frac{\mu_{j,t}}{\max_{j'\in\mathcal{B}^n(t)} \max(\lambda_{j',t},\mu_{j',t})} 1\!\!1_{j\in\mathcal{B}^n(t)}$. The function $f^{(l)}_j$ the expected value of $K_j^{1,(l)}$ when $\max_{j'\in\mathcal{B}^n(t)} \max(\lambda_{j',t}, \mu_{j',t})$ goes to zero. $p_{j,t,l}$ is the probability of the event $\{l_{j,t} = l\}$.

Consequence for wireless networking games The theorem 1 says that under suitable conditions of the learning rate, the above learning schemes can be studied by their differential equation counterparts, and the result applies directly to autonomous self-organizing networks with randomly changing channel states, variable number of interacting users and random updating time slots. Next, we provide our second main result which establishes heterogeneous learning convergence and capture the impact of different behavior of the users.

Theorem 2 (heterogenous rates)**.** *Assume H2-H3 and Assume that the payoff-learning rates are faster than strategy learning rates i.e* $[H4]$ $\lambda_t \geq 0, \nu_t \geq 0,\ (\lambda, \nu) \in (l^2 \backslash l^1)^2,\ \frac{\lambda_t}{\nu_t} \longrightarrow 0.$ *Then, hybrid-delayed-CODIPAS-RL scheme with variable number of players has the asymptotic pseudo trajectory of the following non-autonomous system:*

$$\left\{ \begin{array}{c} \dot{x}_{j,t}(s_j) = g_{j,t} \sum_{l \in \mathcal{L}} p_{j,t,l} f^{(l)}_{j,s_j}(\mathbf{x}_{j,t}, \mathbb{E}_{\mathbf{w},\mathcal{B}} U^{\mathcal{B}}_j(\mathbf{w}, ., \mathbf{x}_{-j,t})) \\ x_j(s_j) > 0 \Longrightarrow \hat{\mathbf{u}}_{j,t}(s_j) \longrightarrow \mathbb{E}_{\mathbf{w},\mathcal{B}} U^{\mathcal{B}}_j(\mathbf{w}, \mathbf{e}_{s_j}, \mathbf{x}_{-j}) \end{array} \right.$$

We define two properties:

• NS: Nash stationary property refers to the configuration in which the set of Nash equilibria of the expected game coincide with the rest points (stationary points) of the resulting hybrid dynamics.

• PC: Positive Correlation property refers to the configuration where the covariance between the strategies generated by the dynamics and the payoff is positive. i.e $F(x) \neq 0 \Longrightarrow \sum_{j,s_j} u_j(e_{s_j}, \mathbf{x}_{-j}) F_{j,s_j}(\mathbf{x}) > 0$ where F is the drift of the dynamics. We say that the expected robust game is a potential game if there exists a regular function W such that $u_j(e_{s_j}, \mathbf{x}_{-j}) = \frac{\partial}{\partial x_j(s_j)} W(\mathbf{x})$.

Theorem 3.

- *(i) If the homogeneous learning are all NSs. Then the heterogeneous learning satisfy (NS)*
- *(ii) If the homogeneous are all (PC) then the heterogeneous are too. (example: Replicator and Smith dynamics). If the potential function serves as Lyapunov in all these dynamics then global convergence holds for the heterogeneous learning.*
- *(iii) The heterogeneous time-scaling leads to a new class of dynamics obtained by composition.*
- *The result of (i) and (ii) extends to hybrid learning (at each active time, the player can select among a set of learning patterns).*

- *(iv) Consider a hybrid of (PCs). If the support of the hybrid learning contains at least one (NS) then the "non-Nash rest points" are eliminated.*

- *(v) the result (iv) extends to evolutionary games.*

Impact of these results for network selection games As stated earlier that in the considered user-centric scenario, the procedures are dynamic in nature and the number of users in the system are randomly changing due users mobility, channel variation, service quality, technologies and protocols evolutions, etc. In many cases, the games have specific structures such as *aggregative games, potential games, supermodular games*. This result gives the convergence of heterogeneous learning to equilibria in dynamic robust potential games but also in dynamic monotone games. Note that these two classes of games include many topology-based network congestion games, network selection games, frequency selection, concave routing games, etc.

8.4 Mean Field Hybrid Learning

The standard learning schemes are limited to the finite and fixed number of players case. As a consequence, the resulting differential equations leads high dimensional system when the size of network is large (such as in internet). In this subsection we show how to extend the learning framework to large number of players called *mean field learning*.

8.4.1 Learning under Noisy Strategy

Following the above lines, one can generalize the CODIPAS-RL in the context of Itô's stochastic differential equation (SDE). Typically, the case where the strategy learning has the following form: $\mathbf{x}_{t+1} = \mathbf{x}_t + \lambda_t(f(\mathbf{x}_t, \hat{\mathbf{u}}_t) + M_{t+1}) + \sqrt{\lambda_t}\sigma(\mathbf{x}_t, \hat{\mathbf{u}}_t)$, can be seen as an Euler scheme of the Itô's SDE:

$$d\mathbf{x}_{j,t} = f_j(\mathbf{x}_t, \hat{\mathbf{u}}_t)dt + \sigma_j(\mathbf{x}_t, \hat{\mathbf{u}}_t)d\mathbb{B}_{j,t}, \tag{8.25}$$

where $\mathbb{B}_{j,t}$ is a standard Brownian motion in $\mathbb{R}^{|\mathcal{A}_j|}$. This leads stochastic evolutionary game dynamics where the stochastic stability of equilibria can be used to find robustness of the system under stochastic fluctuations. Note that the distribution the noisy strategy-learning (8.25) or equivalently the mean field learning can be characterized by a solution of the following partial differential equation called Fokker-Planck-Kolmogorov equation

$$\partial_t m_{j,t}(x) + div(f_j m_t) - \frac{1}{2} trace(\sigma\sigma^t \partial^2_{xx} m_t) = 0. \tag{8.26}$$

where div is the divergence operator and ∂^2_{xx} is the matrix of second derivatives of $m_t(.)$ with the respect to x. Particular case of this class of dynamics are *evolutionary game dynamics with diffusion terms*. We refer to (217) for the derivation of these equations which require the theory of distribution and integration by parts.

8.4.2 Cost of Learning CODIPAS-RL

In this subsection we introduce a novel way of learning under switching cost called *Cost-To-Learn CODIPAS-RL*. Usually in learning in games or in machine learning (reinforcement learning, best reply, fictitious play, gradient-descent/ascent based learning, nonmodel gradient estimation, Q-learning etc), the cost of switching between the actions, the cost of experimenting with another option are not taken into consideration. In this section we take these issues into account and study their effects in the learning outcome. The idea is that *it can be very costly to learn quickly and learning can take some time*. When a player changes its action, there is cost for that. In our scenario, the learning cost can arise in three different situations: (i) handover switch, (ii) codec-switchover, (iii) joint handover-and-codec switch-over. In a more general setting, one can think about a cost to have a new technology or a cost to produce a specific product. The reason for this cost of learning approach is that, in many situations, changing, improving the performance, the quality of experience of a user, guaranteeing to a quality of service etc has cost. At a given time t, if user j changed its selection (codec, handover etc) i.e if user j moves, its objective function is translated form the standard utility plus an additional cost for moving from the old configuration to the new one. Then, there is no additional cost to learn if the action remains the same.

8.5 Application to Heterogeneous Wireless Networks

In this section, we discuss the application of proposed game theoretic learning based approach to network selection and IPTV service provider selection problem.

8.5.1 User-Centric Network Selection

The details about user-centric paradigm may be found in the Chapter 3. We make use of the proposed user satisfaction function proposed in Chapter 2. It should be noted that the assumptions on defining various user types i.e., excellent, good, and fair (for details refer to Chapter 2) is considered.

8.5.1.1 Proposed Architecture for User-Centric Network Selection

We make use of the proposed IMS based architecture (refer to Chapter 3), where the operators implement SIP based services by searching the end-user demands and users have freedom to subscribe to any service provided, the service could be delivered using IMS control plane. The trusted 3^{rd} party entity in the proposed architecture owns non RAN infrastructure such as IMS functional entities including Proxy Call Session Control Function (P-CSCF), Serving Call Session Control Function (S-CSCF), Interrogating Call Session Control Function (I-CSCF), Application server (AS), and HSS(218).

8.5.1.2 OPNET Simulation Setup

The simulation setup for the proposed network selection approach is detailed in Chapter 3.

8.5.1.3 Result Analysis

Within the simulation settings, we configure that all the users in the system have the same *initial probability list* i.e., 0.4, 0.3, 0.2, 0.1 for LTE (Op-1), LTE (Op-2), WLAN (Op-2), and WLAN (Op-1) respectively. We also configure that operator-1 offers lesser service costs when compared with the operator-2, whereas both the operators charge more on LTE than WLAN network technology. The configuration of the technical indices are the same for both the technologies and both the operators, thus the operators offers of technical parameters are influenced by the network congestion, available bandwidth, wireless medium characteristics, etc. The simulation was run for number of iterations and the convergence of user probabilities of network selection was observed for variable learning schemes. First we analyze the behavior of a *fair user* in the given settings, as can be observed in Fig 8.1 that a *fair* user adjusts its probabilities in the given configuration. As expected the user strategies converge (within relatively small number of iterations) so that she prefers the relatively less costly WLAN(OP-1) more than anyother technology, the probability values of other strategies are the consequences of both technical and non-technical offers of the operators. It should be noted that the Fig 8.1 is result in underloaded system configurations i.e., both the technologies of both the operators are under utilized.

We now analyze the *fair user* behavior in the congested system configuration (congested system may defined as the system, where most of the resource are already utilized and the option window of switching the operator (network technology) user is squeezed), the results

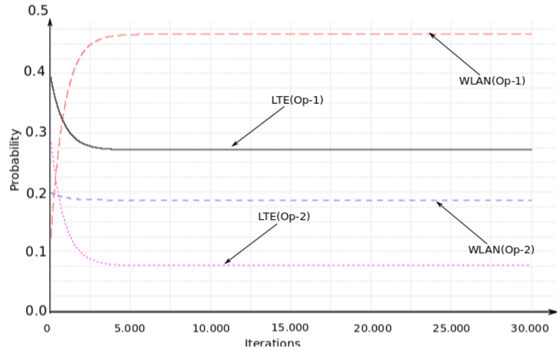


Figure 8.1: Evolution of randomized actions for underloaded configuration - Figure representing the user adaptation of probability distribution for different available strategies in underloaded configuration

for such configuration are presented in Fig 8.2. The impact of congestion over the network selection can be seen by strategy convergence of the user. LTE(Op-2) turns out to be the only underloaded network technology, this shrinks the options of the user and hence the different convergence result than that of underloaded configuration even though the simulation settings remain the similar in both the configurations.

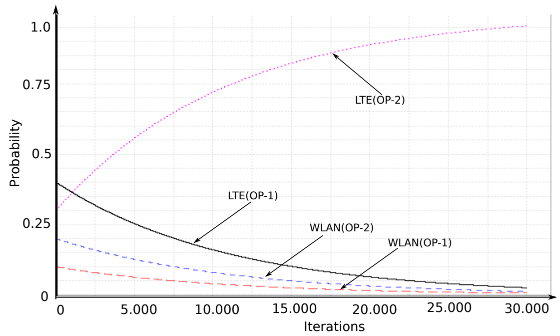


Figure 8.2: Evolution of randomized actions for congested configuration - Figure representing the user adaptation of probability distribution for different available strategies in congested configuration

These results confirm the superiority of the proposed learning approach in user-centric 4G heterogeneous wireless network selection paradigm. A number of simulations were run and various other results in the similar fashion were taken, where service costs were varied, medium impairments (customized impairments were introduced in the wireless medium with the help of *impairment entity*) were introduced in the wireless access networks of different operators. The objective of these scenarios was to analyze the behavior of user decision under various dynamics of the system. All the results follow the similar behavior as the ones shown in Figures-8.1,8.2 in different configurations. Thus on the basis of the presented results we can confidently claim that the proposed learning scheme fits well to the future user-centric wireless networks paradigm.

8.5.2 Frequency Selection and Access Control

In this section, we discuss the network selection in a more concrete environment i.e., concentrating on frequency selection and access control using the proposed learning scheme. We give illustrative example of random medium access control in wireless networks. In wireless communication networks, Medium Access Control (MAC) schemes are used to manage the access of active nodes to a shared channel. As the throughput of the MAC schemes may significantly affect the overall performance of a wireless network, careful design of MAC schemes is necessary to ensure proper operation of a network. Recall the basic rule of slotted Aloha scheme: *if more than two users transmit then there is collision*. Following the idea, one can introduce frequency selection case: *if more than two users transmit at the same time with the same frequency then there is collision*.

We consider n users and m frequencies. $\mathcal{N} := \{1, 2, \ldots, n\}$ is the set of users, n is the total number of users in the system. $\mathcal{F} = \{1, 2, \ldots, m\}$ the set of frequencies for the n users. Each user can choose only one among the m frequencies. Denote by $x_{j,t}(f)$ the probability that user j chooses the frequency f at time t. The success probability of user j is given by

$$u_j(x_t) = \sum_{f=1}^{m} x_{j,t}(f) \prod_{j' \neq j} (1 - x_{j',t}(f)).$$

This says that a user j with frequency f has successful transmission only if no other user is using the same frequency. We examine two cases: (i) $m < n$ (ii) $m \geq n$. The state w corresponds to ON/OFF. The state ON means the interface is working and the state OFF means the interface is not working. When the interface is OFF the user cannot access, therefore we look at the probability for the interface to be ON and multiply the performance index by this probability. In the analysis we omit this probability.

Global optimization

The global optimization problem consists to maximize the probability of successful transmission of all the system. The problem can be formulate as follows:

$$\begin{cases} \max_x & \sum_{j\in\mathcal{N}} u_j(x) \\ & \forall\, j \in \mathcal{N},\ \sum_{f\in\mathcal{F}} x_j(f) = 1 \\ & \forall\, j \in \mathcal{N},\ \forall f \in \mathcal{F},\ x_j(f) \geq 0 \end{cases}$$

We denote by $\Delta(\mathcal{F}) = \{z,\ \sum_{f\in\mathcal{F}} z_j(f) = 1,\ \forall f,\ z_j(f) \geq 0\}$ the simplex. Then, $\forall j,\ x_j \in \Delta(\mathcal{F})$.

- If $n \leq m$, a direct affectation solve the problem. This implies that we have an exponential number of solutions.
- If $n > m$, affect m of the frequencies to m users. The remaining $n-m$ users remains without affectation. We have again an exponential number of solutions.

Equilibrium analysis

Define a one-shot game by the collection $\mathcal{G} = (\mathcal{N}, (u_j(.)_{j\in\mathcal{N}}, \mathcal{F})$. We say that x is an equilibrium of $\mathcal{G}$, is

$$\forall j,\ u_j(x) \geq u_j(x_1, \ldots, x_{j-1}, y_j, x_{j+1}, \ldots, x_n),\ \forall y_j \in \Delta(\mathcal{F}).$$

We first remark that the above solutions of the optimization problem are pure equilibria of the one-shot game $\mathcal{G} = (\mathcal{N}, (u_j(.))_{j\in\mathcal{N}}, \mathcal{F})$. In particular the global optimum value can be obtained as an equilibrium payoff i.e the so-called **Price of Stability** is one.

There are many other equilibria of the game $\mathcal{G}$. To see this, consider the case where $n > m$. Any configuration where all the frequencies are used and any other strategies of the remaining users is an equilibrium of $\mathcal{G}$.

Fairness

When $n > m$ the global optimum and the pure equilibrium payoffs are not fair in the sense that some of the users get 1 and some other 0. A more fair solutions can be obtained using mixed strategies. For example if $\forall\ j, \forall\ f,\ x_j^*(f) = \frac{1}{m}$, the expected payoff of each user is $(1-\frac{1}{m})^{n-1} > 0$ and the total system payoff is $n(1-\frac{1}{m})^{n-1}$.

Pareto optimality is a measure of efficiency. An outcome of the game $\mathcal{G}$ is Pareto optimal if there is no other outcome that makes every user at least as well off and at least one user strictly better off. That is, a Pareto Optimal outcome cannot be improved upon without hurting at least one user.

Lemma 6. *The above strategy profile x^* is Pareto optimal.*

The proof of this Lemma follows from the fact the strategy maximizes the weighted sum of payoff of the users.

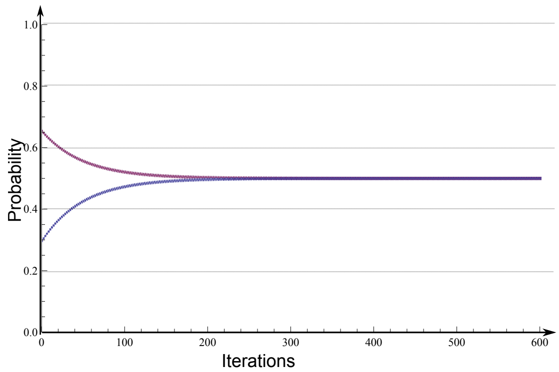


Figure 8.3: Convergence to equilibrium - Figure representing the strategy convergence to the equilibrium state.

Learning Efficient Outcome

As an illustration we have implemented the Bush-Mosteller based CODIPAS-RL. In Fig 8.3 we represent the evolution of strategies in a scenario with two users and same action set $m = 2$, $\mathcal{A}_j = \{1, 2\}$ for the two users. As we can observe, the trajectory goes to an equilibrium $(1/2, 1/2)$ which is not efficient. In Fig 8.4, we represent a convergence to an efficient outcome: global optimum using Bush-Mosteller based CODIPAS-RL for different action sets. Note that, in this scenario the convergence time to be arbitrary close is around is around 250 iterations which is relatively fast.

8.5.2.1 Algorithm

The algorithm CODIPAS-RL is described as follows.

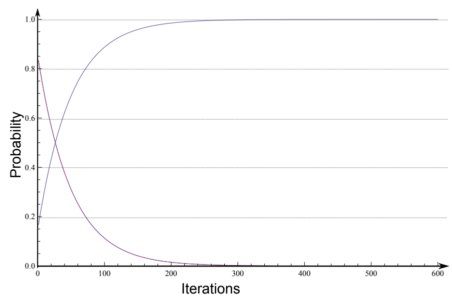


Figure 8.4: Convergence to global optimum - Figure representing the strategy convergence to the global optimum state.

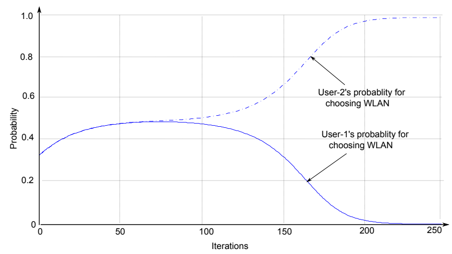


Figure 8.5: Evolution of randomized actions - Figure representing the evolution of randomized strategies of users i.e., either or not choosing the WLAN.

Algorithm 3: Generic representation of the hybrid CODIPAS-RL

foreach *Player* j **do**
    Initial action $a_{j,0}$;
    Initialize to some estimations $\hat{\mathbf{u}}_{j,0}$,;
end
for *t=1* **to** *max* **do**
    foreach *Player* j **do**
        Choose an action $a_{j,t}$ with probability $\mathbf{x}_{j,t}$;
        Observe a numerical value of its noisy payoff $u_{j,t}$;
        Choose one of the learning patterns $l \in \mathcal{L}$ according to ω;
        Update its payoff estimation via $\hat{\mathbf{u}}_{j,t+1}$;
        Update its strategy via $\mathbf{x}_{j,t+1}$;
    end
end

On the similar lines discussed in the *user-centric network selection* paradigm, In Figures 8.5&8.6, we represent the behavior of the users and their estimated payoff when using variable learning schemes. When the users are active, they can select one of the CORDIPAS learning schemes among $\mathcal{L}_1 - \mathcal{L}_5$ with probability distribution $[1/5, 2/5, 1/5, 1/10, 1/10]$. The users are active with probability 0.9. We fix $\lambda_t = \frac{1}{(t+1)\log(t+1)}$. The Figure 8.5 represents the evolution of strategies and the Figures 8.6 and 8.7 represent the estimated payoff evolutions of user 1 and 2. As we can observe, the convergence occurs even for random updating time and hybrid CODIPAS-RLs. Not surprisingly, the convergence time seems very large.

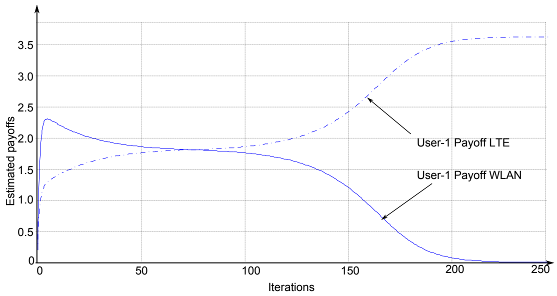


Figure 8.6: User 1: Evolution of estimated payoffs - Figure representing the evolution of estimated payoffs for user-1

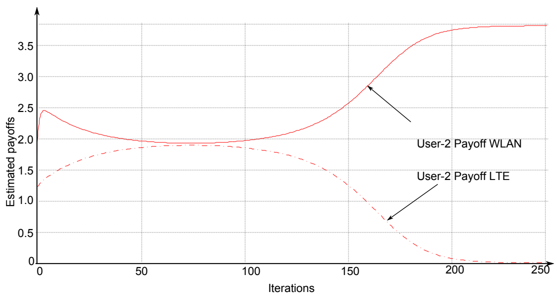


Figure 8.7: User 2: Evolution of estimated payoffs - Figure representing the evolution of estimated payoffs for user-2

8.5.3 User-Centric IPTV Service Provider Selection

When it comes to the measurement of user satisfaction for IPTV services, one is faced with few natural questions. i) How to quantify the perceived user satisfaction with respect to video quality? ii) Does the service cost affect user satisfaction? if yes, how to quantify the user satisfaction with respect to service costs? iii) How to capture user satisfaction with respect to service contents, security, etc. To answer the mentioned questions, we conclude that there is a need to model the user satisfaction function that can quantitatively capture the user satisfaction. In this connection, we use our previous work on user QoE (219).

8.6 User-centric IMS based IPTV Architecture

As explained earlier that the novel user-centric paradigm forces competitive environment with choices between services with different service qualities, service costs, and contents, etc. In the proposed architectural solution, users do not only consume services but also share, recommend and subscribe to the services according to their needs and preferences. The proposed architecture should atleast meet the following requirements; i) supports the 3^{rd} party that negotiates with IPTV service providers / operators on behalf of users for their service requests, and responsible for allocation decision. 3^{rd} party should serve to be the central platform, with which operators create a service level agreement in case operators need to share their resources (However, discussion over such functionality is out of the scope of this chapter). Furthermore it should be responsible for Accounting, Authentication, Authorization, and Billing. ii) Handling handover triggers (i.e., caused by user preferences change, service degradation, service offers change etc.) to ensure the uninterrupted delivery of services to the users. iii) User should maintain a separate business relationship with each SP she has subscribed to. Hence complete user profile should be maintained by HSS of the trusted 3^{rd} party and each SP should receive only the SP specific user data from the HSS.

Given the user-centric IPTV service selection environment, a user is thus faced with the choice of SP selection or/and network infrastructure provider selection. This further discerns three scenarios; i) Given the selected service provider, the decision problem focuses on the network infrastructure provider selection, ii) Given the network infrastructure provider is selected, the decision problem is to select the optimal service provider, and iii) joint service provider and network infrastructure provider selection decision problem.

To meet the mentioned requirements of user-centric service selection paradigm, we propose the IMS based architecture similar to that proposed in Chapter 3. As can be seen a trusted 3^{rd} party is introduced, which is responsible for performing the tasks highlighted in the preceding paragraph. We now detail the functional entities of the proposed architecture, describe theses entities and discuss the integration between them.

It should be noted that in the considered configuration, we address the *fully disintegrated scenario*, where the service providers or content providers are not owned by the network infrastructure providers. However, the proposed analytical framework is rich enough to be applicable to any dynamic scenario.

8.6.1 Architecture Functional Entities, Description, and Their Interaction

In this section, we consider IMS based user-centric architecture similar to presented in Chapter 3.

8.6.1.1 Third Party Functional Entity for IPTV Service Selection

The functional components within this entity are standardized IPTV components that provide *user profile storage*, *service attachment* and *selection* & *service control*. These components facilitate the IPTV service consumers to connect to IPTV networks of several service providers. The IPTV functional components within this entity also interact with a *decision maker* functional component located at third party IPTV service layer. The decision maker component takes care of the optimal service selection decision on behalf of users. We now briefly list the functions of IPTV functional entities as follows: i) Service Discovery Function (SDF), ii) Service Selection Function (SSF), iii) Service Control Function (SCF), and iv) User Profile Server Function (UPSF).

SDF and SSF provide the user with service data such as Video on Demand (VoD) catalogs, EPG and TV channel lists. Therefore, the decision maker functional component collects IPTV service data as offers from several IPTV service providers, aggregates, and selects the best available service provider, which is then delivered to the user in the service attachment and selection process of the UE. The consequence of this process may be the service data consisting of a live TV channel list of service provider A and a VoD catalogue of service provider B. After retrieving the service data the UE is able to select a content item for watching, thus establishes a multimedia session to content providing IPTV service provider. Owing to the fact that users do not have contract(s) with IPTV service providers, SCF has to bridge to IPTV service providers by acting as a Back-To-Back User Agent (B2BUA) in case of a content session establishment.

8.6.1.2 IPTV SP / Operator Functional Entity

Owing to the maturity of current communication paradigm, it is needless to highlight the importance of heterogeneous and their co-existence to extend services to end-consumers. We follow the 3GPP standard for such integration as shown in the architecture shown in Chapter 3. All the operators have IMS core network, IPTV SPs are asked by the 3^{rd} party functional entity to submit the service offers, this dictates that an extended standardized service attachment and selection mechanism may be a possible realization solution. The decision maker component on the 3^{rd} party functional entity acts as IMS SIP client and subscribes for service attachment notifications to the SDFs of the IPTV SPs networks. Besides common service describing content, the notifications have in turn additional service offers relevant information (service costs and provided quality of the service). SP sends new service offers by sending updated notifications to the decision making component residing on the 3^{rd} party functional entity.

8.6.2 Inter-entities Interaction Details

Generally the standardized IPTV procedures for UE start-up and consumer of IPTV content consist of the following steps (220): i) Network attachment, ii) IMS registration, iii) IPTV service attachment, iv) IPTV service selection, and v) IPTV session establishment. We in this work follow the referred procedure for the IPTV service provisioning of the third party network and extend it with the service provider interworking. This comprises of the *service offer and service provider selection initiation* process that takes place during the third step of service attachment. In this step the UE retrieves server addresses and relevant information to access his authorized services, which can thought of as a list of service compiled from the SP service offers. To illustrate this, we present in Fig 8.8 the interaction overview among the entities in a scenario, where the user successively consumes the media of the two different service providers and the figure also presents the details when a change in service offers trigger the decision for the new best service provider.

We now give more details about each procedure in the following subsection.

8.6.2.1 Network Attachment and IMS Registration

After the user switches the UE ON, the IMS registration procedures triggers, and UE attaches to the network of the visited operator network. As UE is not a subscriber to the current operator network, therefore the procedures specific to roaming case is applied. An IMS registration is attempted by sending a SIP registration to the P-CSCF of the operator network which is then forwarded from the operator IMS network to the third party IMS. Thus an IPSec security association is established between the user terminal and the P-CSCF of the operator IMS network that protects all further communication between user terminal and IMS network. On the completion of IMS registration, the user is authenticated with the 3^{rd} party IMS and the available for communication.

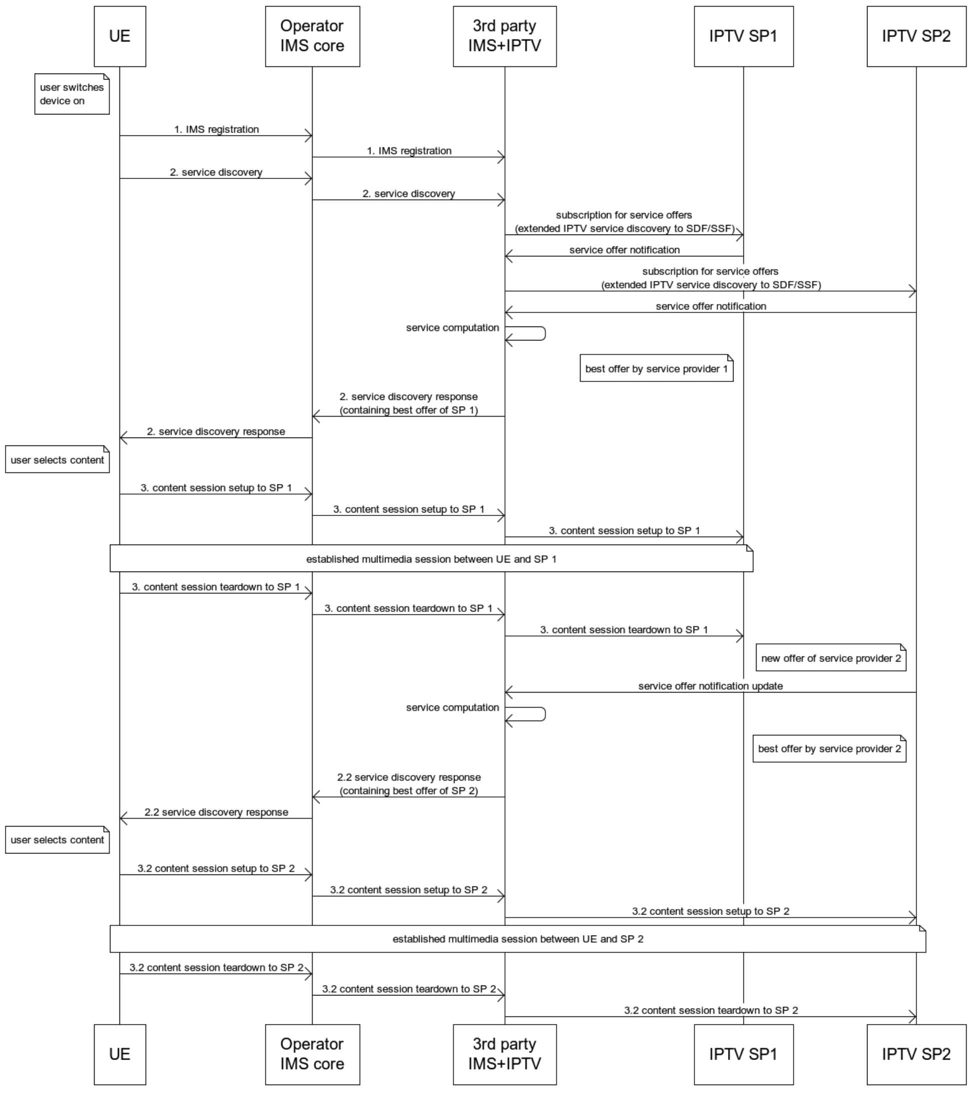


Figure 8.8: Procedures overview - Figure representing the interaction overview among the entities in a scenario, where the user successively consumes the media of the two different service providers.

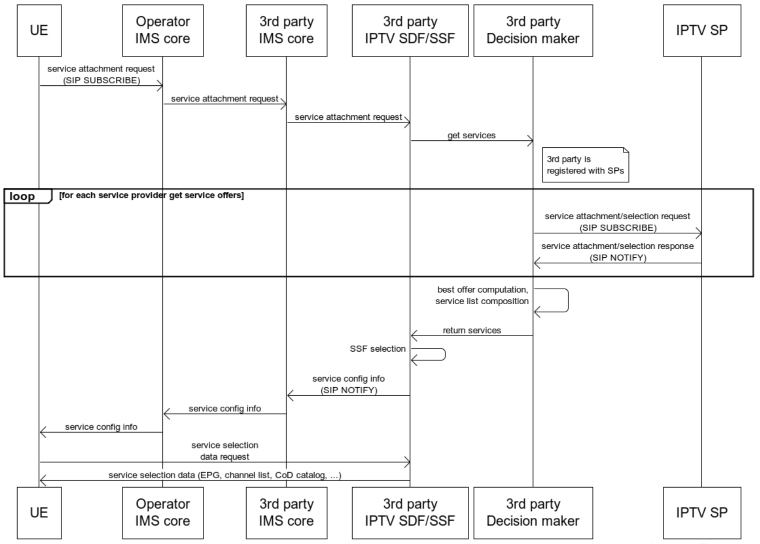


Figure 8.9: Service attachment and selection procedures - Figure representing the IPTV service discovery process

8.6.2.2 IPTV Service Discovery

Fig 8.9 depicts the IPTV service discovery process which is divided in service attachment and selection. This process includes service data allocation from different IPTV service providers as well as the decision making process. In our solution the trusted 3^{rd} party acts on behalf of all users by communicating with IPTV service providers. So the trusted 3^{rd} party owns a subscription with each service provider and we assume that it is successfully registered and authenticated with each IPTV service provider prior to the steps described in the following.

After IMS registration the user equipment performs a standardized IPTV service discovery procedure. The is can be realized by utilizing the SIP SUBSCRIBE / NOTIFY event notification mechanism whereby the NOTIFY provides information about how to retrieve service data such as EPG or VoD lists.

After the trusted 3^{rd} party SDF retrieves service attachment from the UE, it requests the decision maker for service data that is to be delivered to the users. The auction process is triggered by the decision maker, in this configuration, we suggest the reuse of service discovery procedure for the service selection process. Thus the decision maker in turn also acts as an IPTV UE to request the available service data from SDF and SSF functionalities of the IPTV service provider. These SDF and SSF have to be extended by auction bidding like capabilities in a way that the service information they provide is enriched by auction relevant bidding data.

The decision making process starts after getting service data from all IPTV service providers. As the result all service data of the auction winning IPTV service providers is aggregated in documents provided by trusted the 3^{rd} party SSF(s). A notification is then sent from the trusted 3^{rd} party SDF to UE providing the relevant information (i.e., information from the aggregated documents). At this stage, the actual SSF functionality can take place and in an additional filter process such SSF(s) is chosen that matches the user preferences and UE capabilities.

As depicted in Fig 8.8 IPTV service providers can send updated service data offers within the subscriptions between trusted 3^{rd} party and the IPTV service providers (Fig 8.8 shows the whole procedure for two service providers i.e., SP1 & SP2). New offers trigger a new decision maker functionality and result in updated service data notifications to the users.

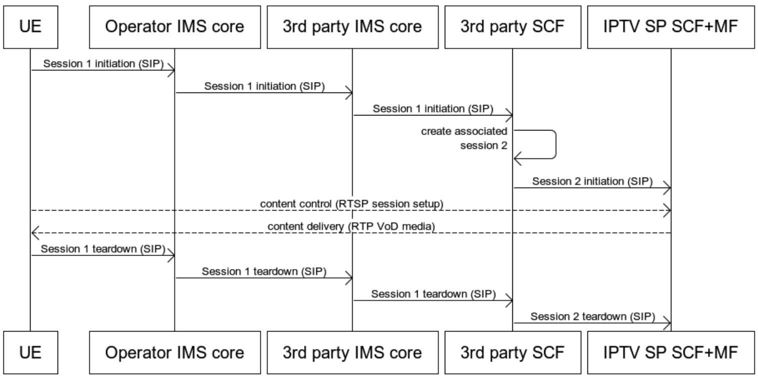


Figure 8.10: Session establishment procedures - Figure depicting the higher level view of the signalling

8.6.2.3 IPTV Session Establishment

Session establishment is performed as depicted in Fig 8.10, which shows the high level view of the signaling and media streaming for a VoD requests. The media resource functions are located in the IPTV service provider network only, but the signaling for media session initiation passes through the IMS networks as well as the SCF of the trusted 3^{rd} party network, this is because only the trusted 3^{rd} party is a registered user of the service provider and acts behalf of the user. Therefore, the SCF acts as a B2BUA and intercepts a user initiated session, creates a new session to the IPTV service providers and stores an association between both for a later intermediation of session signaling (session tear-down). In the new session the originating user is replaced with its own identity registered with the service provider while the destination keeps the same.

8.7 Numerical Analysis

In order to demonstrate the user-centric IPTV service selection, and demonstrate the effect of learning in such a telecommunication landscape, we run extensive rounds of simulation runs. The simulation scenario dictates that IPTV consumers are under the coverage of heterogeneous technologies owned by different infrastructure providers. We consider the LTE and WLAN access network technologies. We extensively implement the integration of these two technologies following 3GPP standards for intra-operator heterogeneous technologies integration. Intra-operator mobility management is carried out using Mobile IPv6. Furthermore in total there are four IPTV service providers, who are considered as potential candidate service providers (competitors) to extend IPTV services to the consumers. Service requests of different quality classes, content types are generated by consumers. The arrival of requests is modeled by Poisson process, and the service quality class is chosen randomly. In order to capture the different consumer preferences we assume that the sizes of different quality class requests are assumed to be static and are 200kbps, 500kbps, and 800kbps for low, medium, and high video quality respectively. The capacities of LTE and WLAN network technologies are 32Mbps (Downlink)/ 8Mbps (Uplink), 8Mbps respectively. As the network technologies are owned by two different operators, the technical configuration of the technologies owned by both the operators are very similar. However, the service pricing scheme is operator specific, which influences the user-centric service selection decision.

Within the simulation settings, we configure that all the users in the system have the same initial probability list i.e., 0.45, 0.35, 0.25, 0.05 for SP-1, SP-2, SP-3 and SP-4 respectively. We also configure that SP-1 and SP-2 offer higher service costs when compared with the SP-3 and SP-4. To capture the system behavior for users preferences over the service costs, we further configure two simulation settings namely i) excellent service settings and ii) fair service settings. In the earlier settings, IPTV users prefer quality over the service costs, whereas the later case is converse to the earlier. Fig 8.12 depicts the results of user strategy convergence in excellent service settings. As can be seen that user initial probability converges such that SP-1 and SP-2 are assigned the equilibrium probabilities of 0.3 and 0.7 respectively, whereas the low quality offering service providers are assigned $zero$ probabilities. On the other hand the initial

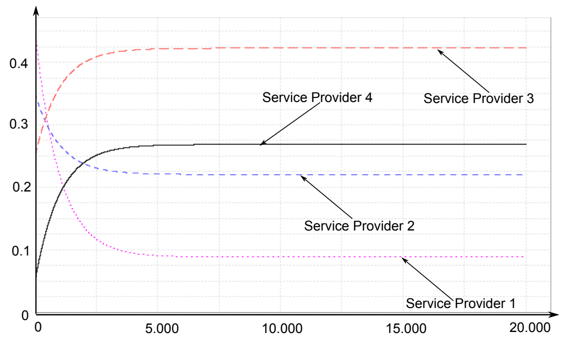


Figure 8.11: Strategy convergence curves of IPTV consumer in fair service settings - Figure representing the strategy convergence to an equilibrium state

strategies of user in Fig 8.11 converge such that user prefers SP-3 and SP-4 more as compared to the other relatively more expensive service providers. However, it should be noted that the decision of service provider selection is based on the user satisfaction function and not only on the cost preferences of the users. The configuration of the technical indices are the same for

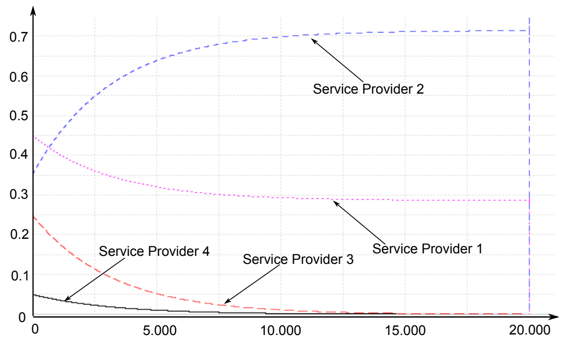


Figure 8.12: Strategy convergence curves of IPTV consumer in excellent service settings - Figure representing the strategy convergence to an equilibrium state

all the underlying technologies, thus the operators offer of technical parameters are influenced by the congestion, available bandwidth, wireless medium characteristics etc. The simulation was run for number of iterations and the convergence of user probabilities of network selection was observed for variable learning schemes. Thus on the basis of the presented results we can confidently claim that the proposed learning scheme fits well to the future user-centric IPTV service selection paradigm.

Comparison with Existing Works in Wireless Networks

Many learning analysis in the literature (182, 184, 207, 212) have been conducted for specific patterns (fixed and the same learning scheme for all the users). The authors in (184) have investigated in detail the convergence and the divergence issues of *equilibria* for the two-user two-action case. However, a payoff-reinforcement learning (also called Q-value learning) is not examined in their models. Our results extends their works to multiple users case about also different updating time, asynchronous changes and random number of interacting users. At this point it is important to mention that in addition to equilibrium analysis, we have established a convergence to a global optimum for our specific 4G network selection problem. To be best to the authors knowledge, very little is known for the convergence to a *global optimum* in a fully distributed learning way (no coordination, no message exchange, only a numerical noisy and delayed measurement of own payoff is observed). Thus, this is very promising result for extension to other specific classes of wireless games. Moreover, using our analysis, the speed of convergence can be improved by choosing constant learning instead of diminishing learning rates. In that case, a weak convergence can be easily established. After that, one can conduct the same analysis for the resulting hybrid evolutionary game dynamics. Finally, the dynamic nature of emerging wireless networks allow us to thing of the importance of time delays, noisy measurement, imperfectness and random number of interaction. The delays can be avoided for appropriate time-scaling. However, for time delay that are learning rate-dependent, *delayed evolutionary game dynamics may arise as asymptotic pseudo-trajectories* (205).

Discussions: Fastest learning algorithm

In this section we address of speed of convergence and running time of simple classes of learning algorithms. The running time analysis is a familiar problem in learning in games as well as in machine learning.

In order to introduce the problem of convergence time, we first start by a classical problem in statistics: Given a target population, how can we obtain a representative sample?

In the context of learning in games, this question can be seen as: Given a list of measurements (such as perceived payoffs), can we obtain a useful information such as best-response strategy or expected payoff distribution?

We consider the class of CODIPAS-RL schemes that generate irreducible aperiodic Markov chain. Let $\mathbf{x}_t$ be an irreducible aperiodic Markov chain with invariant probability distribution

π, having support $\Omega \subseteq \prod_{j\in\mathcal{N}} \mathcal{A}_j$ and let $\mathbb{L}^t$ denote the distribution of $\mathbf{x}_t|\mathbf{x}_0$ for $t \geq 1$. that is

$$\mathbb{L}^t(x,\Gamma) = \mathbb{P}\left(x_t \in \Gamma \mid x_0 = x\right).$$

Then, given any $\epsilon > 0$, can we find an integer t^* such that

$$\parallel \mathbb{L}^t(x,.) - \pi \parallel_{tv} \leq \epsilon, \ \forall t \geq t^*$$

where tv denotes the total variation norm.

Note that, under the above assumptions, $\parallel \mathbb{L}^t(x,.) - \pi \parallel_{tv}$, is non-increasing in t. This means that for every draw past t will also be within a range ϵ from π, thus providing a representative sample if we keep only the draws after t^*. For the Gibbs distributions/Glauber dynamics, there is an enormous amount of research on this problem for a wide variety of Markov chains leading a class of learning schemes in games. Unfortunately, there is apparently little that can be said generally about this problem so that we are forced to analyze each learning scheme chain individually or at most within a limited class of models or situations such as potential, geometric, etc.

To simplify the analysis we focus on the reversible Markov chain case, this is for example satisfied by Boltzmann-Gibbs-based CODIPAS-RL. If $\mathbb{L}_{a,a'}(.)$ denotes the transition matrix and $m = \prod_{j\in\mathcal{N}} |\mathcal{A}_j| = |\mathcal{F}|^n$ the number of action profiles, it is well-known that the convergence time to reach the stationary distribution is governed by the second highest eigenvalue (221, 222) of the matrix $(\mathbb{L}_{a,a'})$ after the eigenvalue 1, Let

$$1 = eig_1(\mathbb{L}) \geq eig_2(\mathbb{L}) \geq \ldots \geq eig_m(\mathbb{L}) \geq -1.$$

The speed of convergence is given by the $\frac{1}{1-eig_2(\mathbb{L})}$. The smaller $eig_2(\mathbb{L})$ is the faster the Markov chain $\mathbf{x}_t$ approaches π.

Based on this observation we define the fastest learning algorithm along the class satisfying the above assumptions as following:

$$\inf_{\mathbb{L}(.)\geq 0} eig_2(\mathbb{L}) \tag{8.27}$$

$$\pi_a \mathbb{L}_{a,a'} = \pi_{a'} \mathbb{L}_{a',a} \tag{8.28}$$

$$\sum_{a'\in\mathcal{A}} \mathbb{L}_{a,a'} = 1, \ \forall a \in \Omega. \tag{8.29}$$

This an optimization problem over the class of learning schemes. Since $eig_2(.)$ is continuous and the set of possible transition matrices constraint is compact, there is at least one optimal transition matrix; the $\inf$ can be by $\min$ i.e an optimal (for the convergence time to π) learning scheme among the class of CODIPAS satisfying the above assumptions exists.

Since we have the existence result, we need to explain how to find this optimal CODIPAS algorithm. This leads to the question of solvability of (8.27). Since the eigenvalue $eig_1(.) = 1$ with eigenvector $(1, 1, \ldots, 1)$, we can write the eigenvalue $eig_2(\mathbb{L})$ as an optimization of a quadratic term over vectors:

$$eig_2(\mathbb{L}) = \sup\{\langle v, \mathbb{L}v\rangle \mid \sum_{a\in\Omega} v_a = 0, \ \| v \| \leq 1\}$$

As a consequence of (221, 222), the convergence time for CODIPAS to be within a range ϵ to π is less than $c(m \log m + m \log(\frac{1}{\epsilon})), \ c > 0$.

8.8 Concluding Remarks

We have presented hybrid and heterogeneous strategic learning schemes in dynamic heterogeneous 4G networks. We have illustrated how important these learning schemes are in wireless systems where the measurement can be imperfect, noisy and delayed and the environment random and changing. Our results are validated through Mathematica numerical examples and OPNET simulations for different service classes over LTE, and WLAN technologies taking into consideration the effect of switching costs in the payoff function. We illustrated the proposed cost of learning CODIPAS-RL scheme to find the corresponding solution in an iterative fashion. Our future work is to extend the heterogeneous cost-to-learn algorithm in the context noisy strategy and randomly varying network topologies.

8.8.1 Proof of Theorem 1

Consider the system of CORDIPAS-RL described in section8.3. Assume the standard assumptions H2-H3 and assume that proportional learning rates (the ratio is relatively similar and non-vanishing). Then, one can write the CODIPAS-RLs in the form of Robbins-Monro's procedure with weighted coefficient and randomly varying number of players. The Robbins-Monro is $\mathbf{x}_{t+1} = \mathbf{x}_t + \lambda_t(f(\mathbf{x}_t) + M_{t+1})$ in $\mathbb{R}^d$ for some $d \geq 1$. To do this, we introduce a reference learning as the maximum for the active users at the current time i.e $\max_{j'\in\mathcal{B}^n(t)} \max(\lambda_{j',t}, \mu_{j',t})$.

Now the learning rate is a random variable. It is easy that this random learning rate satisfies the assumption H3 and it satisfies $\lambda_t \geq 0$, Let $g_{j,t}$ is the limiting of the expected value of $\frac{\lambda_{j,t}}{\max_{j'\in\mathcal{B}^n(t)}\max(\lambda_{j',t},\mu_{j',t})}\mathbb{1}_{j\in\mathcal{B}^n(t)}$. The function $\bar{g}_{j,t}$ is the limiting of the expected value of $\frac{\mu_{j,t}}{\max_{j'\in\mathcal{B}^n(t)}\max(\lambda_{j',t},\mu_{j',t})}\mathbb{1}_{j\in\mathcal{B}^n(t)}$. The function $f_j^{(l)}$ the expected value of $K_j^{1,(l)}$ when $\max_{j'\in\mathcal{B}^n(t)}\max(\lambda_{j',t},\mu_{j',t})$ goes to zero. $p_{j,t,l}$ is the probability of the event $\{l_{j,t}=l\}$.

• The function f is clearly Lipschitz since the polymatrix payoff entries are finite for any subsets of players.

• M_{t+1} is a martingale difference sequence with respect to the increasing family of sigma-fields $\mathcal{F}_t = \sigma(\mathbf{x}_{t'}, \hat{\mathbf{u}}_{t'}, M_{t'},\ t' \leq t)$ i.e., $\mathbb{E}\left(M_{t+1} \mid \mathcal{F}_t\right) = 0$.

• M_t is square integrable and there is a constant $c > 0$, $\mathbb{E}\left(\parallel \mathbb{M}_{t+1} \parallel^2 \mid \mathcal{F}_t\right) \leq c(1+ \parallel \mathbf{x}_t \parallel^2)$ almost surely, for all $t \geq 0$.

• $\sup_t \parallel \mathbf{x}_t \parallel < \infty$ almost surely because remains almost surely in the product of time payoff region by construction. Then, the asymptotic pseudo-trajectory is given by the ordinary differential equation (ODE) $\dot{\mathbf{x}}_t = f(\mathbf{x}_t),\ \mathbf{x}_0$ fixed.

Thus, we can apply the standard approximations developed in Kushner & Clark 1978, which gives that the asymptotic pseudo-trajectory of the hybrid-delayed-CODIPAS-RL can be written in the following form:

$$\left\{\begin{array}{c} \frac{d}{dt}\mathbf{x}_{j,t}(s_j) = g_{j,t}\sum_{l\in\mathcal{L}} p_{j,t,l} f^{(l)}_{j,s_j}(\mathbf{x}_{j,t},\hat{\mathbf{u}}_{j,t}), \\ \frac{d}{dt}\hat{\mathbf{u}}_{j,t}(s_j) = \bar{g}_{j,t}\left(\mathbb{E}_{\mathbf{w},\mathbb{B}^n} U_j^{\mathcal{B}^n}(\mathbf{w},\mathbf{e}_{j,s_j},\mathbf{x}_{-j,t} - \hat{\mathbf{u}}_{j,t}(s_j))\right) \\ t \geq 0 \\ \mathbf{x}_{j,0} \in \mathcal{X}_j, \hat{\mathbf{u}}_{j,0} \in \mathbb{R}^{|\mathcal{A}_j|}. \end{array}\right.$$

8.8.2 Proof of Theorem 2

The proof follows assimilar line as in theorem 2 but using multiple time-scale stochastic approximations.

8.8.3 Sketch Proof of Theorem 3

Now, we provide a sketch proof of Theorem 3. To prove the theorem 3, we use tools from hybrid evolutionary game dynamics. We want to rely the outcome of dynamics with the equilibria of the expected robust game. (i) Assume that the homogeneous learning are all NSs. Then the zeros of the heterogeneous dynamics of best response of the homogeneous. Thus, they are best response and the resulting dynamics satisfy (NS).

(ii) If the homogeneous are all (PC) then the heterogeneous is PC by summation of positive terms. Thus, the expected game is a potential game and if the potential function serves as Lyapunov in all these dynamics then global convergence holds for the heterogeneous learning.

(iii) The heterogeneous time-scaling leads to a new class of dynamics obtained by composition of the drift terms. This new class of dynamics may be some convergence properties that the homogeneous learning may not have. This proves that the heterogenity is crucial for the convergence. The results of (i) and (ii) extends to hybrid CODIPAS-RL by taking the sum over all the learning patterns in the support. (iv) If an hybrid of (PCs) contains at least one (NS) then the "non-Nash rest points" are eliminated. This is because such a point cannot be a rest point of the resulting hybrid dynamics. (v) the result (iv) extends to hybrid evolutionary game dynamics with large number of players (possibly continuum), see (223). This completes the proof.

9

Coalition Formation in Network Selection

The widespread use of heterogeneous wireless technologies, their integration, advent of multi-mode terminals, and the envisioned user (service) centricity enable users to get associated with the best available network(s) according to user preferences and application specific requirements. When it comes to user-centric network selection, operators with the view to increasing their user-pool may offer different incentives to the users e.g., reduced service prices, better service quality, or attractive packages to motivate them form coalitions. In this chapter, we focus on the user coalition formation in the user centric paradigm, we present a novel approach of coalition network selection. We use evolutionary game-theoretic approach to model this problem. We also examine fully distributed algorithms for global optima in network selection games. Then, the problem of dynamic network formation and evolutionary coalitional games in network selection are investigated. This article also points out the open research issues, new interests and developments in this interdisciplinary field.

9.1 The Point of Interest

Most of the earlier research literature concentrating on user-centric network selection focuses a single user network selection decision making e.g., (224, 225, 226, 227, 228, 229, 230, 231) , whereas the research literature concentrating cooperation at the operator level (e.g., (150, 151, 152, 168, 173)) is mostly network centric and do not consider the user-centric paradigm. It is envisioned that in future communication paradigm the users will be able to form coalitions.

Thus opening a new front, which we term as the *coalitional network selection*.

As discussed in the earlier chapters, for over two decades, classical game theory has been intensively applied in wireless networking and communications (232, 233). For instance, the application of game theory concepts to CRRM problem has been considered using both cooperative ((2, 160)) and non-cooperative / competitive ((115, 116, 117)) game models to obtain efficient resource allocation schemes, where as (74, 234), etc. use game-theory to model network selection problems. However, as the wireless nodes become mobile, more autonomous, self-organizing, self-configuring, and the access networks are more decentralized, the associated mathematical tools need to be adapted. Since one-shot game models (cooperative or not) do not allow to update strategies, do not allow error corrections, the game theorists have proposed dynamic game theory. These include stochastic games, evolutionary games, differential games and their ramifications. Dynamic game theory (181) is a more appropriate framework and captures more the behaviors of future envisioned wireless networks where randomness, time delays and uncertainty are present. One of the dynamic game theoretic modeling is *evolutionary game theory* (EGT). It goes back at least to the works by Fisher (1930), Hamilton (1964), Maynard Smith (1972). For more details on evolutionary game dynamics, we refer to (235). Following our argument on the need and justification of *evolutionary game theory* to future wireless networks, we converge attention to the application of dynamic games to the cooperative user behavior in future user-centric scenario. This dictates the use of coalitional evolutionary game-theory for modeling the user-centric coalition formation and coalition network selection problems. Many researchers are currently engaged in developing evolutionary game theory based schemes in large-scale wireless networks that allows to describe evolution of cooperation, evolutionary network formation, dynamic network security, evolution of protocols, network neutrality, random graph-based topology and architectures. When it comes to application of standard coalition game models to wireless networks, we are confident to claim that the current research is restricted to applying standard coalitional game models and techniques to study very limited aspects of cooperation in wireless networks. At the same time, the implementation of coalitional games in large-scale wireless networks encounters several challenges such as appropriate modeling, efficiency, stability, signalling reduction, complexity, fairness, incomplete information and mobility management.

To the best of author's knowledge, this work is the amongst the first contributions that focuses on user-centric coalition network selection and apply the evolutionary game theoretic concept to user-centric network selection approach. We also briefly discuss the coalition formation at the operator level. We make use of *dynamic coalitional games* for the proposed coalition network selection approach. Dynamic coalition game is a very promising tool for designing fair, robust, practical, and efficient adaptive coalitional strategies in wireless networks where the network conditions evolve dynamically (i.e., backoff state, channel sate, arrival of users, departure of users, etc.). The evolutionary coalitional game modeling is one of the dynamic coalitional game framework. It is very powerful framework inspired from biology, genetics and evolutionary ecology.

9.2 Contribution

Our contribution can be summarized as follows:

- We first present the evolutionary ingredients that constitute the fundamentals of evolutionary coalitional games as well as their potential applications in wireless networking and communications in general, and coalition network selection in special.

- Second we provide a better understanding of the current research issues in this emerging direction. After that we develop a dynamic process that describes the evolution of coalition in terms of incoming flux and outgoing flux.

- Finally, we attempt an investigation into pertaining design constraints and outline the use of evolutionary dynamics tools to meet certain design objectives.

9.3 Basic Ingredients of Evolutionary Game-theory

The basic ingredients of evolutionary (coalitional or not) game theory are the solution concepts (equilibrium and its refinement such as *evolutionary stability*) and *evolutionary game dynamics*. Below we describe these two key elements.

9.3.1 Equilibrium and Refinement

In this subsection, we detail the equilibrium and stability concepts of evolutionary games.

9.3.1.1 Equilibrium Concepts

Evolutionary networking games in large systems provides a simple framework for describing strategic interactions among large number of players (mobile terminals, base stations, access points, users etc). Traditionally, predictions of behavior and outcome in game theory are based on some notion of equilibrium, typically Cournot equilibrium (Cournot, 1838), Bertrand equilibrium (Bertrand, 1883), conjectural variation (Bowley, 1924), Stackelberg solution (Stackelberg, 1934), Nash equilibrium (Nash, 1951), Wardrop equilibrium (Wardrop, 1952), mean field equilibrium or some refinement and/or extensions thereof. Most of these notions require the assumption of equilibrium knowledge, which assume that that each player correctly anticipates how the other players will react. The equilibrium knowledge assumption is too strong and is difficult to justify in particular in context with large number of users in dense networks.

9.3.1.2 Evolutionary Stability

An evolutionarily stable state or strategy (ESS) is a population profile which, if adopted by a population of players, cannot be invaded by any alternative population profile of small size. An ESS is an equilibrium refinement of the Nash equilibrium – it is a Nash equilibrium which is evolutionarily stable meaning that once it is fixed in a population, it is resilient to invasion by small fraction of the population. Other refinement have been explored in evolutionary games: unbeatable state, neutrally stable state, non-invadable state, risk-dominant state or payoff, correlated evolutionary stable state, evolutionary stable set , stochastically stable state, continuously stable state, global evolutionarily stable state (GESS, the analogue of ESS for multiple population games).

9.3.2 Evolutionary Game Dynamics

As an alternative to the equilibrium approach, the evolutionary game approach proposes an explicitly dynamic updating choice, a model in which players myopically update their behavior in response to their current strategic environment. This dynamic procedure does not assume the automatic coordination of players' actions and beliefs, and it can derive many players' actions and transition rates. These procedures are specified formally by defining a revision of pure strategies called revision protocol. A revision protocol takes current costs (expected performance) and the system state as arguments; its outputs are conditional switch rates which describe how frequently players in some class playing strategy who are considering switching strategies switch to another strategy, given that the current expected cost vector and subpopulation state. This revision of pure strategies is flexible enough to incorporating a wide variety of paradigms, including ones based on learning, imitation, adaptation, optimization, etc. The revision of pure strategies describe the procedures players follow in adapting their behavior to in the dynamic evolving environment such as evolving networks (Internet traffic, flow control, etc.). Simple evolutionary game dynamics are replicator dynamics, Brown-von Neumann-Nash dynamics, fictitious play, adaptive dynamics, imitate the better dynamics, best response dynamics, logit or Boltzmann-Gibbs or log-linear dynamics, Smith dynamics, projection dynamics, gradient methods, generating (G-)function based dynamics, evolutionary game dynamics with diffusion, evolutionary game dynamics with migration, spatial evolutionary game dynamics with migration and time delays.

9.4 Overview of EGT in Wireless Networking

The evolutionary game dynamics approaches have been applied in IEEE 802.16 (208), in wireless mesh networks (236), resource pricing (237), P2P soft Security incentive mechanism (238). It has been applied to hybrid rate control in (239). In (185), routing games and their fast convergence algorithm designs have been studied using replicator dynamics.

Evolutionary games in wireless networks have been studied in (240) with particular emphasis to application of *delayed evolutionary game dynamics*. The idea of time delayed payoffs in dynamic games is the following: usually it is assumed that the users (players) receive their payoffs instantaneously (also highlighted in Chapter 8). However, in many realistic scenarios, the observations are delayed with some time unit. In the context of wireless networks, this can be due to feedback delays, noise, propagation delays, etc. To capture this phenomenon, time delays have been introduced into evolutionary game dynamics. This means that an action taken today will have its effects after some time delays. Therefore, the payoffs are delayed. The idea has been applied in (241) access control and power control in both IEEE 802.16 OFDMA-based wireless networks (WiMAX) and Code Division Multiple Access (CDMA) based networks.

9.4.1 Convergence Issue

Evolutionary game dynamics provide a powerful tool for prediction of the outcome of a game. Convergence to equilibria has been established in many classes of games. These include generic two-users-two-actions games, common interest games, potential games, sub/super-modular games, many classes of aggregative games, games with unique evolutionarily stable strategy, stable games, games with monotone payoffs, etc., see (235). As a consequence convergence issue of several networking problems including parallel routing, routing with M/M/1 cost (Poisson arrival process, exponentially distributed service time and single server queue), network congestion games, network selection games, power allocation games, rate control, spectrum access games, resource sharing games, and many others, can be investigated through evolutionary game dynamics for both linear and non-linear payoff functions.

9.4.2 Selection Issue

A fundamental question we address now is the selection problem (equilibrium, Pareto optimal solutions, global optimum, etc.) in a *fully distributed way* (minimal signalling to the users, no message exchange, no recommendation, etc.).

9.4.2.1 How to Select an Efficient Outcome?

The problem of selection of a global optimum in a fully decentralized way is a very challenging problem. To the best to the authors knowledge, very little is known in this way. In the next section we provide examples of games where fully distributed reinforcement learning algorithms lead to evolutionary game dynamics that converge to global optima. However, in general in evolutionary game dynamics, the convergence issues are examined for equilibria.

9.4.2.2 How to Select a Stable Outcome ?

Another important question is the stability/instability of the system. How to design fast algorithms such that a network that behave well after some iterations? This question will be translated by the fact that when time horizon is large, the behavior of the system looks like at a stationary and any small perturbation around this point will quickly come back to that point due to losses. It is important to mention that the two properties: *Stability* and *Efficiency* may not be compatible in some situations.

9.4.3 Fully Distributed Reinforcement Learning

As explained in Chapter 8, from most of the evolutionary game dynamics one can construct fully distributed learning algorithms where the users can adapt its strategy in an iterative fashion without knowing the mathematical expression of its payoff function: *only numerical mea-*

surement will be observed by the user as it is usually done in machine learning. Now, each player needs to learn its own payoff function and its optimal strategy in parallel. This type of learning scheme is called *combined fully distributed payoff and strategy reinforcement learning* (CODIPAS-RL, (242)). Using standard stochastic approximations tools, the asymptotic pseudo-trajectories of these schemes can be relied to the evolutionary game dynamics possibly time-dependent, delayed and noisy. The basic representation of CODIPAS-RL updating scheme has the following form:

$$\text{Newstrategy} \longleftarrow \text{Oldstrategy} + \text{Stepsize (learning-rule - Oldstrategy)} \tag{9.1}$$

$$\text{Newestimate} \longleftarrow \text{Oldestimate} + \text{Stepsize (Target - Oldestimate)} \tag{9.2}$$

where the target and "learning-rule" play the role of the current strategy and current measurement/observation. The expression [Target - Oldestimate] is an error in the estimation. It is reduced by taking a step size towards the target. The target is presumed to indicate a desirable direction in which to move. Well-known examples of strategy-learning are based on Bush & Mosteller (1955, (191)) learning schemes and their variations. These schemes have been extended to stochastic games using Bellman's dynamic programming (Bellman, 1952, (243)) and Shapley principle (Shapley, 1953, (244)). More recent applications to engineering can be found in (182, 184). Most often the limiting behavior of the stochastic iterative schemes are related to the well-known evolutionary game dynamics: multi-type replicator dynamics, Maynard-Smith replicator dynamics, Smith dynamics, projection dynamics, imitation dynamics, etc.

9.4.4 Application of Evolutionary Games to Network Selection Problem

In this section, we detail the application of evolutionary game theory to our problem of network selection. We start with relatively simple case (i.e., APs of different frequencies selection) and then model the novel coalition network selection at two levels namely *operator level (the configuration in which operators from coalition(s), we briefly discuss this)* and *user level (the configuration in which users form coalitions)*. Both these configurations are further detailed later in this section.

9.4.4.1 Simplified AP Selection Problem

Let us consider a scenario, where a user is under the coverage area of two APs operating at different frequencies. We assume that access technologies are interference limited i.e., user associating with an AP affects the quality of already associated users to this AP. In order to grab the crux of the proposed approach, we simplify the problem to a two player game, however it

1\ 2	f_1	f_2
f_1	(0,0): collision	(1,1): success
f_2	(1,1): success	(0,0): collision

Table 9.1: Strategic form representation of 2 nodes - 2 choices

1\ 2	f_1	f_2
f_1	(0,0,0)	(0,1,0)
f_2	(1,0,0)	(0,0,1)
1\ 2	f_1	f_2
f_1	(0,0,1)	(1,0,0)
f_2	(0,1,0)	(0,0,0)

Table 9.2: Strategic form representation for 3 users - 2 frequencies

should be noted that the model and solution is still scalable to $n-$number of APs / users. We assume that each user can select one of APs at a time, when both the users select the same AP at the same time instances, without the loss of generality, we assume that both the users will end-up with $zero$ utility. The $zero$ utility can be interpreted as the consequence of the collision and data loss. Table 9.1 represents the matrix form of the stated scenario, where row players correspond to users and the column players represent APs.

As can be observed that the game has two pure equilibria (f_1, f_2) (f_2, f_1) and one fully mixed equilibrium $(\frac{1}{2}, \frac{1}{2})$ which is also evolutionarily stable strategy in the sense that it is resilient to deviations by small change of investment. The fully mixed equilibrium is less efficient in terms of social welfare. The pure equilibria are *Strong equilibria* (robust to any coalition of any size). The two pure equilibria are maxmin solutions in the sense that the minimum payoffs of the users is maximized. It is easy to see that the two pure equilibria are also global optima. Now, a natural question is, *Is there a fully distributed learning scheme that converges to global optima?* The answer to this question is positive for most of the initial conditions in the two-users-two-choices. The set of initial conditions under which convergence to global optima is observed is of measure 1.

Let x_t denotes the probability for user 1 to choose f_1 at time t, and y_t the probability for user 2 to choose f_1 at time t. Using the iterative scheme

$$x_{t+1} = x_t + \lambda_t u_{1,t} \left(1\!\!1_{\{a_{1,t}=f_1\}} - x_t \right) \tag{9.3}$$

$$y_{t+1} = y_t + \lambda_t u_{2,t} \left(1\!\!1_{\{a_{2,t}=f_1\}} - y_t \right) \tag{9.4}$$

one can find the asymptotic pseudo-trajectory for $\lambda_t = \lambda$ constant (convergence in law) or for time-varying λ_t satisfying $\lambda_t > 0, \ \sum_{t'} \lambda_{t'} = +\infty, \sum_{t'} \lambda_{t'}^2 < +\infty$. The term $1\!\!1_{\{a_{1,t}=f_1\}}$

represents the indicator function. It is equal to 1 if the user 1 has chosen f_1 at time t i.e $a_{1,t} = f_1$ and 0 otherwise.

Theorem 4. *The algorithm given by the system (9.3) and (9.4) can be tracked asymptotically by a solution of a differential equation:*

$$\dot{x} = x(1-x)(1-2y), \tag{9.5}$$

$$\dot{y} = y(1-y)(1-2x), \tag{9.6}$$

Proof. By standard stochastic approximations one can show that the rescaled process from (x_t, y_t) is asymptotically close to a solution of some differential equation. Here we identify the exact differential equation.

To obtain this, we compute the expected change in one-time slot, also called drift:

$$\mathbb{E}\left(\frac{x_{t+1}-x_t}{\lambda_t} \mid x_t = x, y_t = y\right) = x(u_{1,f_1}(y) - xu_{1,f_1}(y) - (1-x)u_{1,f_2}(y)) = x(1-x)(u_{1,f_1}(y) - u_{1,f_2}(y))$$

where $u_{1,f_1}(y)$ is the expected payoff obtained by user 1 when she uses f_1 and user 2 plays a randomized action $(y, 1-y)$. It is easy to easy $u_{1,f_1}(y) = 1-y$ is the probability that user 2 chooses f_2. Similarly, $u_{1,f_2}(y) = y$. Thus,

$$\mathbb{E}\left(\frac{x_{t+1}-x_t}{\lambda_t} \mid x_t = x, y_t = y\right) = x(1-x)(1-2y)$$

We do the same work for y_t. Since we work in the unit square, the gap between the expected term and the random variable is a martingale difference. Moreover the norm of this martingale is bounded by the norm of (x, y). We deduce that the following result:
The asymptotic pseudo-trajectories give the replicator dynamics.
If x denotes the probability for user 1 to choose f_1 and y the probability for user 2 to choose f_1 then the ordinary differential satisfied by x and y are:

$$\dot{x} = x(1-x)(1-2y), \tag{9.7}$$

$$\dot{y} = y(1-y)(1-2x), \tag{9.8}$$

□

Define rest points (or stationary points) of the system as the zeros: $\dot{x} = 0, \dot{y} = 0$.

Theorem 5. *The set of rest points of the dynamics contains both the set of equilibria and the set of global optima.*

Proof. The rest points of the system are obtained by finding the zeros of the right hand side of the system. The zeros are $(0,0),(1,0),(0,1),(1,1),(\frac{1}{2},\frac{1}{2})$. Thus, the set of equilibria of the game $\{(1,0),(0,1),(\frac{1}{2},\frac{1}{2})\}$ is in the set of rest points. The set of global optima $\{(1,0),(0,1)\}$ is also in the set of rest points □

Theorem 6. *Starting from any point in the unit square* $[0,1]^2$ *outside the segment* $y=x$ *and* $y=1-x$, *the system converges to the set of global optima.*

This result gives global convergence to efficient point (global optimum) for almost all initial conditions. We say almost all initial points because the diagonal and the anti-diagonal segments are of Lebesgue measure zero (in two dimension) compared to the measure of the square $[0,1]^2$.

Proof. By computing the Jacobian at each of the 5 rest points, we check that $(1,0)$ and $(0,1)$ are stable, and other 3 rest points are unstable (the Jacobian have a positive eigenvalue). Then, we built the vector field of our dynamical system. Starting from any point in the unit square $[0,1]^2$ outside the segments $y=x$ and $y=1-x$, the system converges to the corner $(1,0)$ or to $(0,1)$ depending if the starting point is more at the left corner or the right corner. We conclude that the system converges to one of the global optima $\{(1,0),(0,1)\}$. □

As a corollary, we deduce that by well-choosing the learning parameters, say $\lambda_t=\frac{1}{5+t}$, the fully distributed learning algorithm converges almost surely to global optima, which is a very interesting property.

Now, what happens if the starting points are in the diagonal or anti-diagonal segments? The cases corresponds to symmetric configurations and the system is reduced to one dynamical equation

$$\dot{x}=x(1-x)(1-2x).$$

We say that $x^*=(x^*_{f_1},x^*_{f_2})$ is an evolutionarily stable strategy if for any $x\neq x^*$ there exists an $\epsilon_x>0$ such that

$$\sum_{f\in\{f_1,f_2\}}(x^*_f-x_f)u_f(\epsilon x+(1-\epsilon)x^*)>0,\ \forall\epsilon\in(0,\epsilon_x).$$

The following theorem conducts the analysis of the symmetric case.

Theorem 7. *Now, we consider symmetric configuration.*

- *the symmetric game has a unique evolutionarily stable strategy which is given by* $(\frac{1}{2},\frac{1}{2})$.
- *the system goes to the unique evolutionarily stable strategy starting from any interior point* $x_0\in(0,1)$.

Proof. In symmetric configurations, the evolutionarily stable strategies should be symmetric equilibria. Thus, we have to check among the set of symmetric equilibria which is reduced to $(\frac{1}{2}, \frac{1}{2})$. We verify that $(\frac{1}{2}, \frac{1}{2})$ satisfies

$$(\frac{1}{2} - x, \frac{1}{2} - (1-x)) \binom{1-x}{x} = (\frac{1}{2} - x, -\frac{1}{2} + x) \binom{1-x}{x} = (\frac{1}{2} - x)(1 - x - x) = 2(\frac{1}{2} - x)^2$$

which is strictly greater than 0 for any $x \neq \frac{1}{2}$. We conclude $(\frac{1}{2}, \frac{1}{2})$ is an evolutionarily stable strategy (ESS). Since $\frac{1}{2}$ is a global attractor at the interior, the dynamic system converges global to $\frac{1}{2}$ starting from any point $x_0 \in (0, 1)$. This completes the proof. $\square$

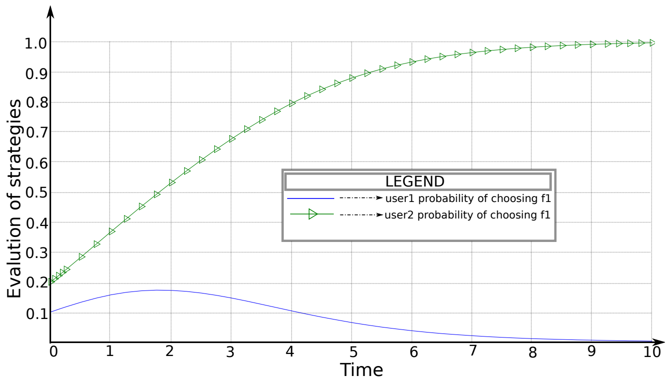


Figure 9.1: Imitation convergence - Convergence to global optimum using imitation dynamics.

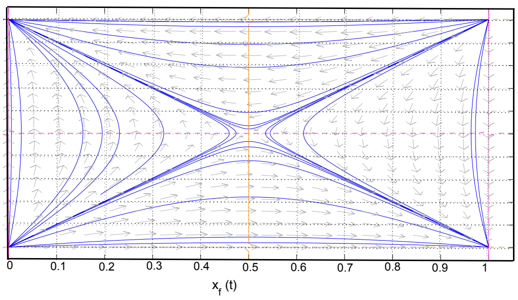


Figure 9.2: Vector field of imitation dynamics - Figure providing with the description of all the possible trajectories starting from the unit square.

The results for the mentioned network selection problem are presented in Figures 9.1 and 9.2. Fig 9.1 illustrates the convergence to global optimum of the network selection problem and Fig 9.2 shows all the possible trajectories (vector field). Except the diagonal and the anti-diagonal segments, all the trajectories lead to a global optimum. We further illustrate the solution results under imitation dynamics in Fig 9.2 and in Fig 9.3 under replicator dynamics.

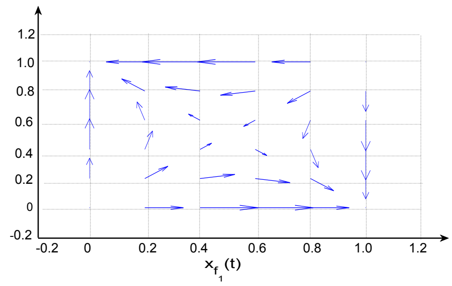


Figure 9.3: Replicator dynamics - Vector field of replicator dynamics.

Next we give an example for three users. Now, there are less resources than users so that there will be always a collision at one of the positions. The case of 3 users and 2 frequencies yield to the matrix form as shown in Table 9.2. In this case the global optima are (f_1, f_1, f_2) and (f_2, f_2, f_1) and their permutations i.e., (f_1, f_2, f_1), (f_2, f_1, f_1), (f_2, f_1, f_2), and (f_1, f_2, f_2). Thus, as can be seen that there are 6 six optima.

9.5 Evolutionary Coalitional Games in Wireless Networks

In this section, we present the analytical framework based on the coalitional game-theory approach. As envisioned that stake-holders in future user-centric network selection paradigm may *decide to pool their resources* (bandwidth, infrastructure resources, etc.) in case of operators or *generating a combined coalition service request* in case of users. The motivation for coalition at both levels is driven by the objective function maximization of both the stake-holders i.e., users and operators. Coalitional game theory can be used for modeling any form of confederation, alliance or wireless network community formation. We devise techniques by which entities autonomously decide whether it is profitable or costly to coalesce. This needs an exploration of the resulting aggregate cost or payoff of a coalition is allocated among participant entities (using dynamical Shapley value or any other imputation procedure that are time-varying and time-consistent) and will characterize the space and properties of allocations such that immunity to coalition formation is guaranteed. Thus, we will understand rules that enforce or discourage coalition formations, depending on whether coalition is to enforce (such as when multiple entities collaborate in an overlay network) or to defend against (e.g., an instance of a collusive malicious action). This will enable a precise prediction of network behavior and lead to network engineering where entities will enjoy high utility and no one is harmed. Different performance objectives need to be explored at different levels, such as QoE at the user level, which is the function of achievable throughput, service cost and other QoS parameters including delay, packet loss, and jitter. We contribute with the utility based user QoE representation (refer to Chapter 2). Plugging the values of different parameters one can get the estimated QoE for any real-time and non-real-time applications. It should be noted that the study of coalition formation games and their evolution is of particular interest, especially in cases where the bit-level intricacies encountered in wireless networks are taken into account, as captured by information theory. Advanced receiver and spatial processing designs, novel means for treating interference and the possibility of mixing separate traffic streams through network coding will allow for an information theory-modulated coalitional game theory and a characterization of the set of network operational points that are achieved by coalition formation and negotiations. Coalitional game theory in wireless networks have been widely investigated in the literature (245, 246, 247). We refer the reader to the recent tutorial in (248) and the references therein.

Since cooperative game theory is concerned primarily with coalitions, one of the problems is how to divide the utility among the members of the formed coalition. The basis of this theory was laid by John von Neumann & Oskar Morgenstern (1944) with coalitional games in characteristic function form, known also as transferable utility games (TU-games). The theory has been extended to non-transferable utility games (NTU-games).

The formation of coalitions, their values and the long-run evolution of coalition play an important role in opportunistic networks (249) and in reputation systems, etc. Most of the literature in communication networks dealing with cooperative games and formation of coalition do not address the issues related to the dynamic solution concept (over time and randomness). Most conflict situations are not "one-shot" coalitional games but continue over some time horizon (finite or infinite). This work, however, deals also with the evolution of coalitions. Since network selection problems are dynamic in nature, one needs to adapt the classical coalitional game approach to *dynamic coalitional game theory* in order to capture the realistic behaviors that describe the networks. The idea of evolutionary coalitional games have been examined recently in (249) for access control problems.

We focus on myopic dynamics of such games inspired from evolutionary game dynamics. One of the advantages to use evolutionary framework for coalition formation is that the dynamic process describes both the formation of new coalitions and the strategic interaction between users and coalitions or between coalitions. The class of evolutionary game dynamics that we use here need less information compared the standard repeated game approaches (245).

Under suitable assumptions, evolutionary game dynamics gives naturally some algorithms for finding equilibria, stability conditions, limit cycles, and chaotic behaviors.

We describe the formation of coalitions and their evolutions by an explicit process based on revision of allocation of users and coalitions. Using these evolutionary processes one can show that the survival of a coalition in long-run and the long-term topology depends on the investment of each member of the coalition, users allocations, and the initial coalitional structures.

9.5.1 Formation of Adaptive Coalitions

With the different levels of interaction (between users, between coalitions, between single user and coalitions, etc.), the analysis of the dynamical system can be quite complicated for a larger number of users and coalitions. The dynamics will be essentially determined by the rules for selecting or changing the allocation of payoffs to a particular coalition, and from the coalitions to the joint actions which are evaluated by the members. At each time t, distribution of coalition values and costs to its members is subject to negotiations between them. A single user j has the rule β for joining J' from $J : \beta^j_{J,J'}(x(t), u(t))$ where $x(t)$ is an allocation vector at time t, $x^j_J(t) \in [0, 1]$ represents the investment of user j in coalition J. The evolution of coalitions is given by the difference between the incoming flux and the outgoing flux

$$\dot{x}^j_J(t) = inflow - outflow \tag{9.9}$$

where the inflow is given by $\sum_{J'} \beta^j_{J',J}(x(t), u(t))x^j_{J'}(t)$ and the outflow is $x^j_J(t) \sum_{J'} \beta^j_{J,J'}(x(t), u(t))$.

The incoming flux to J corresponds to the arrival investment rate to J and the outgoing flux from J is the departure investment rate from J. Note that, this is different than the population dynamics formulation since it is not based on the proportion of users. Here x corresponds to a coalitional investment.

$$\begin{aligned} \dot{x}^j_J(t) &= \sum_{J'} \beta^j_{J',J}(x(t), u(t))x^j_{J'}(t) - x^j_J(t) \sum_{J'} \beta^j_{J,J'}(x(t), u(t)) \\ &:= V^j_J(\beta, x(t), u(t)) \end{aligned} \tag{9.10}$$

An important class of rules is the class of pairwise comparison of estimates with the current target. In it each time, each user chooses an investment based on a function of $u^j_{J'}(t) - u^j_J(t)$ i.e.,

$$\beta^j_{J',J}(x(t), u(t)) = \xi^j \left(u^j_{J'}(x(t)) - u^j_J(x(t)) \right)$$

where $\xi^j : \mathbb{R} \longrightarrow \mathbb{R}_+$ is positive function. $\xi^j(\gamma) = 0$ if $\gamma \leq 0$.

Using the work in (241) (Chapter 2), we get the following result: Any stationary point x_J^j of the process satisfies:

$$x_J^j > 0 \Longrightarrow u_J^j(x) = \max_{J'} u_{J'}^j(x)$$

This means that in the long-run if the process converges to a stationary point, then the stationary point is locally optimal. Moreover, convergence of the process is guaranteed(241) if the value of the assignment per coalition generated monotone mapping i.e.,

$$\sum_J (x_J^j - y_J^j)(u_J^j(x) - u_J^j(y)) \leq 0.$$

Now that we have defined the framework for evaluating coalition games, we illustrate the concept by a simplified example. The choice of the example is dictated by its similarity in behavior to that of our core coalition network selection problem. Modeling the problem using coalition evolutionary game and solving it, we then generalize the results to coalition network selection problem.

9.5.2 Example: Evolutionary Coalitional Spectrum Access

In cognitive radio networks, the unlicensed secondary users are required to sense the channels in order to detect the presence of the licensed primary users and transmit during periods where the primary user is inactive. Since a single user is not able to sense several channels simultaneously, coalitional spectrum sensing can improve the sensing performance of the secondary users and then decreases the interference on the primary users. For performing dynamic coalitional spectrum sensing and reducing collision, secondary users can locally form a coalition that may evolve over time due to mobility and the outcomes. In each coalition of secondary users, a rule of sensing a set of channels will be jointly used. If a secondary user member of some coalition J is unhappy of its success transmission during several slots, she can leave this coalition and then join another coalition according its probability of success and sensing efficiency. Her decision will affect the coalitional structure that forms in the network.

We address the following questions:

- Suppose that the new group is forming, will the others nodes be motivated to form further new coalition(s)?
- Where will all this lead in the long-run?

- What will be the final topology of coalitions?

These questions are further illustrated and addressed in the numerical examples.

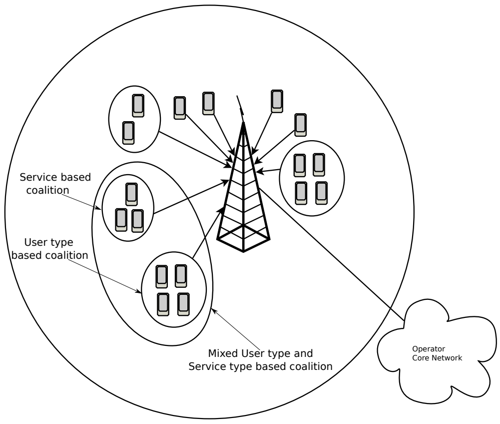


Figure 9.4: Scenario - Figure representing a simple coalitional secondary network

9.5.2.1 Coalition Formation by Replication

Let β be the rule of changes or joining the coalition and is proportional to the investment times the instantaneous regret then the dynamics in (9.9) becomes the replicator dynamics. As in standard replicator dynamics, $x_J^j(t)$ increases with the payoff of a coalition J for the user j, compared to the average payoff. Thus those coalitions that better serve the single users' interests will grow more. The main difference with the standard *replicator dynamics* is that we have individual players rather than populations, and $x_J^j(t)$ represents an allocation (not a fraction of players). Using the evolutionary game dynamics with migration developed in (241) allows us to apply the methodology from this field, including equilibrium and evolutionary stability concepts.

To illustrate this, we consider the spatial distribution of wireless nodes and receivers given in Fig 9.4. We took the initial coalitions as $J_1 = \{1, 2\}, J_2 = \{3, 4\}$ and $J_3 = \{5\}$. We distinguish two ingredients for the value of a coalition. The first part includes the spectrum sensing efficiency in order the improve the probability of success and the second part is of cost for energy consumption (for both sensing and transmission). When transmitting, one can express the outcome for the coalitions J_1, J_2, and J_3. $u_{J_1} = -c_S - c_T + (1 - x_{J_2})(1 - x^5)$, $u_{J_2} = -c_S - c_T + (1 - x_{J_1})(1 - x^5)$, $u^5 = -c_S - c_T + (1 - x_{J_1})(1 - x_{J_2})$ where c_S is the energy consumption cost for sensing and c_T represents the transmission cost of a single packet.

Below we look at the evolution of coalition starting from this initial conditional structure. We fix $c_S = 1/8, c_T = 1/2$. The evolution of coalitions is represented in Figures 9.5 and 9.6.

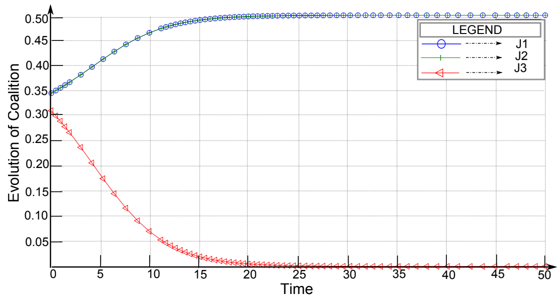


Figure 9.5: Evolution curves - Figure representing the evolution of the coalition starting from $(0.34, 0.34, 0.32)$

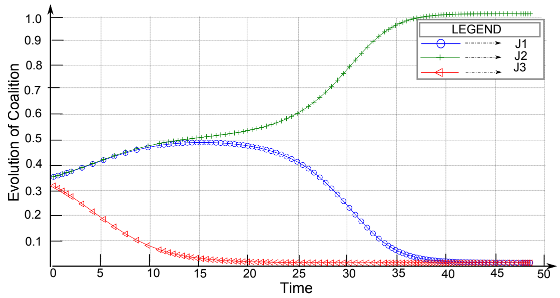


Figure 9.6: Evolution curves - Evolution of the coalition starting from $(0.345, 0.346, 0.309)$.

We observe in these figures that user 5 is interested to join one of the coalitions or stay quiet. We examine the case where user 5 joins to coalition J_1, J_2 or will act selfishly. Then, we have three configurations: $J_1 = \{1, 2, 5\}, J_2 = \{3, 4\}$ or $J_1 = \{1, 2\}, J_2 = \{3, 4, 5\}$ or the initial configuration. In the new network formation the coalition J_3 disappears. The Figures 9.7 and 9.8 illustrate the new formation of coalition.

These numerical examples show that small changes in the initial conditions can lead to very different results in the coalitions formed of the game. The endogenous formation of coalition and long-term stability depends on the existing coalitional structure.

9.6 Coalitional Network Selection in 4G networks

Having explained the vision of future wireless networks in the preceding chapters, one can expect a tighten competition among the future wireless service operators. The expected intense

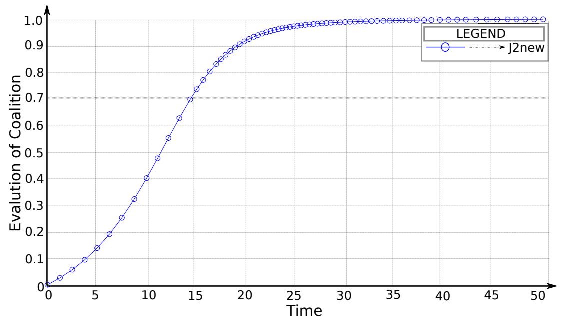


Figure 9.7: Evolution curves - Evolution of coalition depending on the investment of user 5

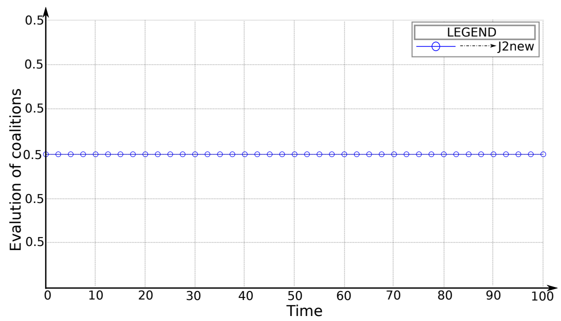


Figure 9.8: Evolution curves - Evolution of the coalition when user invests equally: fuzzy coalition .

competition among operators can be scaled over two dimensions i.e., competitive and cooperative dimension. The earlier is straightforward, where the operators compete particularly in tariff. The consequence of tariff competition is the increased traffic volume of usage which in turn forces operators to increase their network capacities in order to maintain quality. Going forward, however, the tariff war may recede owing to the fact that it will need high capacities and hence large funding requirements for CAPEX. However, the case of interest for this chapter is the later case, where the competition forces operators cooperation.

9.6.1 Competition Enforces Operators Cooperation

Its is expected that the intense competition could force the future wireless industry to consolidate in the form of business cooperation. Putting this straight, some (or all) of the operators in a geographical coverage area enter into an agreement for resource sharing specific to geographical area. Although such cooperative resource sharing may be found in the current telecommunication landscape, however these cooperation approaches address the issue of enabling operators for (inter)national roaming. The novel scenario that we consider in this chapter is the operators cooperation in the user-centric framework. Given that the users are delegated with the decision of network selection, we briefly comment on formulation the operator cooperation model on the similar lines explained in the earlier exampels.

9.6.1.1 Operator Level Cooperation in User-Centric Paradigm

It is known from dynamic games that in presence of perfect monitoring, perfect recall and under regularity conditions, emergence of cooperation can be observed in non-cooperation interaction. The operators can form a coalition and share their revenue and cost. Then we formulate a cooperative game among operators. Assuming transferable payoffs, we use the Shapley value.

• Let $S_{\mathcal{N}}$ be the set of permutation $\mathcal{N}$. Let $\pi \in S_{\mathcal{N}}$. The set $p_{\pi,j} = \{j' \in \mathcal{N}, \mid \pi^{-1}(j') < \pi^{-1}(j)\}$ consists of all predecessors of k with respect to the permutation. The marginal contribution vector at time t, $m_{\pi,j,t} \in \mathbb{R}^{\mathcal{N}}$ with respect to π and v has the j-th coordinate

$$m_{\pi,j,t}(v_t) = v_t(p_{\pi,j} \cup \{j\}) - v_t(p_{\pi,j}),\ j \in \mathcal{N}$$

• The Shapley value Φ of a game v_t is the average of the marginal vectors of the game: $\Phi(v_t) = \frac{1}{n!} \sum_{\pi \in S_{\mathcal{N}}} m_{\pi,t}(v_t)$

The formation of coalition among the operators is similar to the dynamic formation process described in subsection 9.5.1.

9.6.2 Users Coalition Formation

It is believed that with user-centric approach in place, operators with the view to increasing their user pool follow different strategies by offering differentiated services, service price offers, discount packages, etc. In order to illustrate more over this envisioned approach, we list the following potential case scenarios of future wireless network paradigm (one may think of many other potential use cases, we presented in the following few general ones).

- In a business meeting with a number of participants, where the participants will prefer forming a grand coalition and select a network operator that incentivize the participants in terms of service charges or service quality. In this case the services and user types may be homogeneous.

- In a teleconferencing of a research project among different partners, the participants of the conference will be happier to utilize the service of the operator(s) who offers heterogeneous services (VoIP, TCP based FTP, etc.). Operator(s) offerings may be influenced by the user types and service types, thus operator(s) incentivize the participants by offering various attractive offers to encourage the users form coalition(s). It should be noted that operator(s) incentives are specific to their target user market segments.

- A group of friends or family members trying to attain telecommunication services on lower prices by forming coalitions, etc.

It should be noted that in all the highlighted scenarios, the decision of user joining the coalition is influenced by the QoE of users (142), which in turn is driven by the operators' offers. Thus operators in a way have the controlling lever to increase their user pool in form of service and cost offers. Intuitively an under-loaded operator is motivated to attract different size(s) of coalition than an over-loaded operator. Since the user QoE comprises of *technical* and *economic* components, we therefore carry out extensive simulations to investigate the impact of coalition size(s) on user QoE with respect to technical indices only. The reason for dropping the economic aspect from simulation analysis is the following; we believe that extensive simulation results will capture the environment dynamics (wireless medium characteristics, technology specific behavior, interferences, etc.) and their impact on the user coalition size(s). Once we know the impact of coalition size on user QoE specific to technical indices, the impact of varying economic parameters (different service prices, etc.) is straightforward and studied by many researchers in the research literature. Thus we, in this section, emphasize more on the evaluation of technical indices.

9.6.2.1 Simulation Setup

In this section, we detail our OPNET Modeler 15.0 based simulation setup. We consider the wireless coverage footprint of two operators. Both the operators own LTE access network technology in the coverage area. The operators' technical potential in the considered coverage area is exactly the same i.e., both operators deployed the access technology, backbone resources, and core network facilities are similar. We now detail the technical specifications of the access technology.

9.6.2.2 LTE Configuration

The considered LTE operates in $10MHz$ spectrum frequency with the cell coverage of $500m$ radius. There exists only one cell per eNodeB. The observed cell throughput in the downlink is $13Mbps$(with all FTP users offering very heavy traffic load). Background offered load is considered to be $\sim 2Mbps$, which is mapped on Guaranteed Bit Rate (GBR) bearers with QoS Class Identifier (QCI)-1. The MAC scheduling is performed using *Round Robin*. We configure 1 bearer per UE (1 application per UE). Owing to the fact that we are investigating multiple applications running in a UE with each application provisioning different QoS. For instance the applications ensuring *minimum guaranteed bit rate bearers* have an associated GBR value for which dedicated transmission resources are permanently allocated (e.g., by an admission control function in the eNodeB) at the bearer establishment / modification. However, the applications which do not guarantee any particular bit rate, no bandwidth resources are allocated permanently to the bearer. For the proposed approach, where FTP users subscribe for different data rates with operators, which in turn define the user types e.g., excellent users are subscribed to transmission resource ranges $[r^{exc}_{min}, r^{exc}_{max}]$, where $r^{exc}_{min} \geq r^{good}_{max}$, etc. We therefore map FTP traffic to QCI-9. Following the user subscription assumption for non-GBR traffic, we make use of the *Aggregated Maximum Bit Rate* (AMBR) parameter, which refers to the maximum bit rate allowed for all the non-GBR SDFs aggregated for a UE. We enforce this parameter in the downlink, however it can also be implemented in the uplink direction but it is out of the scope of this work, since we are concentrating on the QoE analysis for downlink traffic. The AMBR in this simulation set up is set as $1.5Mbps$(per UE for non-GBR bearers only). We further assume that users are mobile in the coverage area and in the simulation this is carried out by selecting the *Random way point* model and setting the UE speed (walking speed) $0 - 1.4m/s$, which is uniformly distributed. We also configure the user mobility pause time as uniformly distributed between $0 - 30seconds$. We configure the LTE transport network as all ethernet $1Gbps$ links with DiffServ enabled on the last-hop router, where VoIP is mapped to EF PHB and FTP is mapped to BE PHB. In this case we do not introduce any IP impairments. We use the most commonly used flavor of TCP i.e., *new Reno* with the buffer size of $65535bytes$ and window scaling disabled. In order to avoid congestions at the Uu interface, Call Admission Control (CAC) is performed when total offered load (FTP + VoIP) reaches $10Mbps$ per cell. The user downloads the TCP based FTP file of (2Mbytes). The generation of user request is modeled using *poisson distribution* and the inter requests duration is normally distributed with the mean 14. There are 14 FTP users and 6 VoIP users in total in the system. It should be noted that VoIP users generate the background load.

9.6.2.3 Simulation Configurations

In order to investigate the performance of the proposed coalitional approach and its impact on the user QoE, operators call blocking rate and resource utilization in different simulation configurations. By configuration here we mean different simulation settings, which are explained as below.

- *Single user - no coalition configuration:* This setting dictates that no coalition can be formed and users within the system select the network operator that increases their individual utility functions i.e., user QoE. User request generation follows the Poisson distribution and call holding time is configured as the file size i.e., $2Mbps$.

- *Partial coalition - (4+2) configuration:* This setting dictates that coalition of two different sizes are allowed i.e., either of 2 or 4 users.

- *Near grand coalition - (5+1) configuration:* This setting dictates that a nearly grand coalition is allowed i.e., 5 users are allowed to form a coalition leaving one user in case of simultaneous user connectivity.

9.6.3 Results and Analysis

We decompose the analysis into operator specific and user specific analysis. Within the operator specific analysis, we investigate the performance of the approach in terms of *call blocking*, *resource utilization*, and *amount of accepted calls*, etc. However, user specific analysis focuses on evaluating the performance in terms of DRT and achievable datarate (which can be translated in users' QoE). These analysis are carried out for all the mentioned configurations. The aim of such decomposition is to evaluate the performance of the proposed coalition based approach in terms of the parameters specific to the objective functions of different involved stake-holders.

Remark 16. *The fact that TCP sharing available bandwidth evenly is valid in the simulation scenario because all configuration parameters e.g., TCP parameters, traffic priority at transport network and at MAC schedular, etc. have been configured in the similar way. Moreover all users on the average enjoy good channel condition to avoid any possible throughput degradation due to bad channel quality. Aforementioned effect is achieved by restricting user movements in an area near eNB.*

9.6.3.1 Single User - No Coalition Configuration

This section mainly focuses on the evaluation of the proposed approach for user specific and operator specific analysis in terms of different parameters.

Operator specific analysis - We observe from the simulation results that at any time instance the maximum number of accepted FTP calls do not exceed 6 (the number of accepted calls is influenced by the simulation settings), which advocates that CAC takes care of system congestion avoidance and any additional request is dropped. We also observe that within this configuration, on average both the operators behave the same in terms of accepted calls. This is illustrated by the Fig 9.9, as can be observed that in *no-coalition* configuration, operator-1 has 7.8% more active calls when compared with operator-2. However, in the other configurations, somewhat similar active call pattern by both the operators is observed. It should be noted that the number of accepted calls in *grand coalition* and *partial coalition* configurations are confined to below 200 calls due to greater bandwidth allocation per call (illustrated later in this section).

Fig 9.11 and Fig 9.10 represent the average resource utilization and call blocking rate of both the operators respectively. As can be observed that almost in all the configurations, the resource utilization and call blocking patterns of both the operators remain in close proximity to each other. Similar to the observation we made for accepted calls analysis in the preceding paragraph, operators in *no-coalition* configuration block the least number of calls and most calls are blocked in *grand coalition* configuration, behavior is also influenced by the request size(s).

User specific analysis - The user QoE can be captured by DRT and average data rate. Although at this stage, we can transform the throughput / datarate into QoE following the transfer function in (142), we stick to the datarate and DRT to infer the user satisfaction owing to the fact that datarate and DRT in all configurations are comparable. However, we also analyze the user perceived QoE (after application of transformation and utility function as in (142)) in Table 9.3. Fig 9.12 represents the average user DRT i.e., $13.2sec$ for all the configurations. It should be noted that the average DRT values in all the configurations are influenced by the user subscription to the operators for FTP application, where it is assumed that calls are admitted only if the minimum required bandwidth is allocated to the users. Fig 9.13 represents the average datarate of a user, where it can be seen that user datarate is restricted by imposing the bandwidth shaping rate on non-GBR traffic of a user at IP layer level. This shaping rate is equal to the maximum subscribed datarate for a particular FTP request between user and operator. In case of congestion, the TCP connections strive to share available bandwidth resources evenly(as explained earlier). In this case the user may experience throughput lesser than maximum expected data rate. However, in order to avoid congestion in the system CAC is necessary.

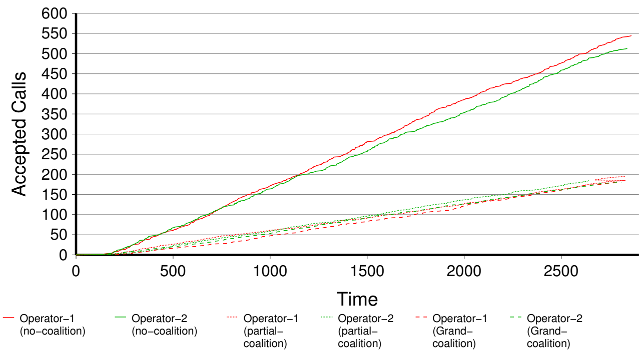


Figure 9.9: Curves representing the amount of active calls - Number of active calls by both the operators in all the configurations.

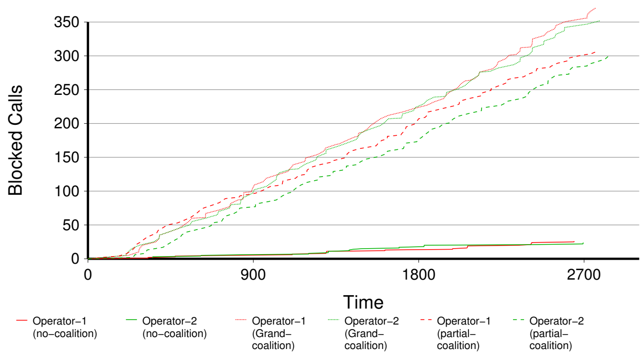


Figure 9.10: Blocked calls - Curves representing the amount of blocked calls in all configurations.

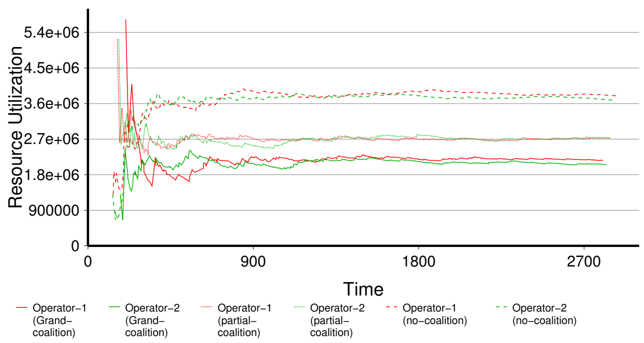


Figure 9.11: Curves representing operators' resource utilization - Operators' resource utilization in all configurations.

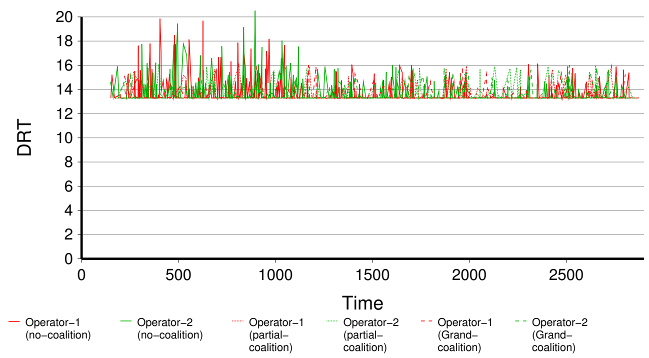


Figure 9.12: User DRT curves - Figure representing user DRT values for all the configurations.

9.6.3.2 Partial Coalition Configuration

We investigate the impact of coalition formation on the similar lines as in the case of *non-coalition* settings. For the sake of clarity, we abuse the term *user request* here as the *coalition request*, where the *coalition request* can take any definition influenced by the size of coalition e.g., the aggregated request of two users in case of coalition size of two users will be termed as *coalition request*.

The objective of coalition formation at the user end is driven by the objective function of increasing their utility functions e.g., user QoE, whereas at the operator end it is driven by the objective functions of operators.

Operator specific analysis - To evaluate the operator specific performance evaluation parameters, consider Fig 9.9, 9.10 & 9.11 for accepted calls, call block rate, and resource utilization respectively. It is observed from Fig 9.9 that the accepted calls by operator 1 are almost 33.6% of the calls it accepted in *no-coalition* configuration. Similarly operator-2 accepts 37.5% of the total accepted calls in the *no-coalition* configuration. On the similar lines, comparison of the call block rates of no-coalition and partial coalition (as shown in 9.10) reveals a great increase in the call blocking rate in the later configuration, as also highlighted in Table 9.3. This phenomenon is intuitive, as in the current settings, the call request size is greater than that of no-coalition settings. The coalition request size determines the resource allocation unit, here by the unit, we mean the lower bound of the requested bandwidth by the user. Thus the greater the resource unit is, the higher is the probability of call being blocked i.e., this depends on the operators' accommodation of incoming requests. This directs us to analyze the operator resource utilization, which could directly be translated into operator revenue. We then analyze resource utilization of operator, which is depicted in Fig 9.11, as can be seen that the resource utilization pattern of both the operators are similar and converge to an average of $2.7Mbps$, which when compared with no-coalition scenario shows that a decrease of 25%.

User-specific analysis - From Fig 9.12 it can be observed that the DRT is in the proximity of 13, which is almost similar to DRT (13.3) observed in *no-coalition* scenario. The arguments presented in no-coalition settings are equally valid for analysis in this configuration.

9.6.3.3 Nearly-grand Configuration

In this setting the coalition request size somewhat approaches 80% of the operator available resources.

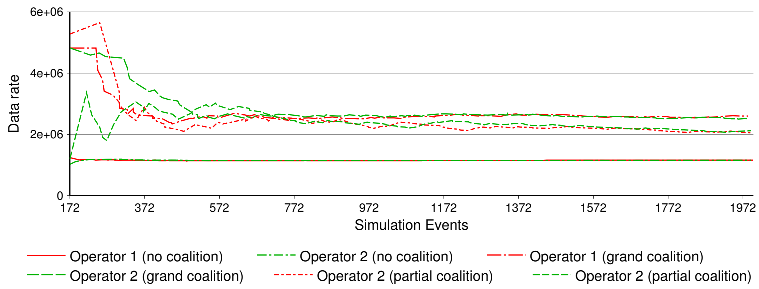


Figure 9.13: Curves representing users' datarate - User Datarate (throughput) in all configurations.

Operator specific analysis - Observing the active calls in Fig 9.9, a reduction of 32.7% and 35.2% is noted for operator-1 and operator-2 respectively, when comparing it with *no-coalition* settings. Reduction of 0.02%, 0.07% in active calls of operator-1 and operator-2 is observed respectively, when comparing it with the partial coalition settings. On the similar lines comparing the call blocking rate of the near grand coalition to rest of the two settings yield that the call blocking of near grand coalition lies very near to that of partial coalition settings. It is interesting observation, a relatively bigger amount of call blocking rate than that of partial coalition setting was expected, but the call comparison of the two settings reveal that both the settings have somewhat similar behavior in terms of call blocking. However, when it comes to the comparison of resource utilization, the Fig 9.11 shows that on average the operator resource utilization in this case is around $2.2Mbps$, which is 57% and 81% of the resource utilization of no-coalition and partial coalition settings respectively.

User-specific analysis - The Fig 9.12 advocates that the DRT in this setting is the same as in the previous two settings. Similarly the average user data rate remains within the same bound as that of the previous two settings.

Remark 17. *We note that when coalition is formed, the operators are then faced with following situations:*

- ***When operators are fully under loaded:*** *Operators can accept a coalition request of both types i.e.,* 2 *users / coalition and* 4 *users / coalition. The operators are motivated to incentivize the users and in turn increase their resource utilization.*
- ***Operators are entertaining coalition requests with*** 2 ***users / coalition:*** *Operators, when under-loaded and implementing the policy of admitting coalition request of 2 users*

/ coalition, are motivated to entertain both the types of coalitions i.e., 2 & 4*, as this may lead to increasing their gain in terms of resource utilization.*

- ***Operators are currently entertaining a coalition request with*** 4 ***users / coalition:*** *Operators implementing the policy of* 4 *users / coalition will be motivated to accept requests of 2 users / coalition or single user requests in situations when the operators' current available resources are not enough to entertain the requests of* 4 *users / coalition.*

The above observations dictate that operators' resource utilization is liable to reduce owing to large blocks of bandwidth requests by coalition i.e., the greater is the request size might not fit into available bandwidth resource of the network. Such a restriction is not experienced in the *no-coalition* settings.

On the basis of above analysis, we are confident to conclude that given the mentioned service and user types, the coalition size has no impact on the user perceived QoE i.e., as observed the DRT and average throughput of users in all the configuration remains unchanged. However, the coalition size has impact on the operator resource utilization, call blocking and in turn on operators' revenue. Thus the controlling lever for motivating the users to form coalition may be the service cost offers by the operators e.g., by offering discounts when operators are willing to encourage the coalition formation. The amount of discount is influenced by the operator status e.g., the under-loaded operators offer higher discount on formation of coalition, however the coalition size(s) is typically decided by the operator resource capacity or operator policy. On the other hand an over-loaded operator would discourage coalition by equating the discount factor $zero$.

9.7 Challenges and open issues

The evolutionary coalitional game approach can be extended in different ways:

- stochastic coalitional population games to allow modeling the variability of users' internal states such as backoff state, battery-state, modulation scheme, resource state characteristics, etc.

- In emerging wireless networks, the architecture, the topology structure and the performances depend on different layers, the upper layers performance depend on the lower layers performance and vice versa, an appropriate framework for such a scenario would be coalitional hierarchical population games with different types of users.

Table 9.3: Utility control parameter values for VoIP and FTP applications

Parameter	Configuration	Operator-1	Operator-2
QoE	No Coalition	4.305	4.250
	Partial coalition	4.237	4.213
	Near grand coalition	4.14	4.186
Call blocking	No Coalition	24	26
	Partial coalition	310	300
	Near grand coalition	370	360
Resource utilization	No Coalition	3.8Mbps	3.8Mbps
	Partial coalition	2.7Mbps	2.7Mbps
	Near grand coalition	2.2Mbps	2.2Mpbs

- Imperfectness and time delays are frequent in wireless networks where the measurements can be noisy, outdated and need to be approximated. In presence of randomness, robustness and incomplete information, the framework needs to be extended to robust coalition games and evolutionary coalitional games with incomplete information.
- In this chapter, we have presented single value per coalition but one can extend the modeling to multiple objectives, leading multiple objective evolutionary coalitional games.

9.8 Conclusion

We have shown that the use of simple tools of evolutionary game theory can lead to global optimum of technology selection games and more generally in anti-coordination games in a self-organizing and fully distributed manner. We have demonstrated how evolutionary games can be extended to *evolutionary coalitional games* and we provided the use of this new tool to emerging wireless networks. We have observed that the survival of a coalition in long-run and the long-term topology depends on the investment of each member of the coalition and the initial coalitional structure of the network. In our ongoing work, we plan to apply evolutionary coalitional games in heterogeneous and hierarchical wireless networks.

10

Conclusion

At the beginning of this work, we set the goal of addressing the following research question, *"How to realize an end-to-end efficient user-centric telecommunication paradigm?"* In terms of major contributions, the thesis models interactions among different telecommunication stake-holders, proposes various mechanisms in form of algorithms, and suggests system wide learning approaches. The basic requirements in this direction include defining the envisioned roles of stake-holders, their relationships, and their objective functions. We believe that in the future user-centric and dynamic telecommunication paradigm, all the involved stake-holders are in a way interdependent and thus influence the decision making strategies of one another. This provisions the concrete definition of stake-holders, their positions in the telecommunication value chain model, their relationship(s) with other stake-holders, their objective functions, etc. We started with modeling the user-satisfaction function for different application types in Chapter 2 with the view to proposing an analytical function that realistically estimates satisfaction of users. This requirement led us to validate the proposed satisfaction against the subjective and objective measurement methods, which we did and concluded that our proposed user satisfaction function realistically estimates the user satisfaction (with appreciable confidence level). Given the fact that users may have short term contractual agreements with operators and user satisfaction function is public knowledge, the obvious decision making instance between users and operator turns out to be network selection. We modeled such user-centric network selection decision using auctioning theory and suggested the architectural realization solution in Chapter 3, this chapter also encamp the proposed solution to problem of frequent handovers. The contributions so far discussed would have been adequate, had the wireless market not introduced the concept of DSA and new entrants i.e., we are faced with few more stake-holders, few more relationships, and few more dependencies. Obviously, neglecting the new market (i.e., the market comprising of network providers, MVNOs, and Spectrum traders, etc.) while modeling decisions at different levels may not result in desired system efficiency. This leads us to study the new market, the stake-holders within the new market, roles of these stake-holders, and discuss the relationships of these stake-holders in Chapter 4. Now that the new market is also defined, we propose the user-centric network selection mechanism in the broader telecom domain with different dynamic markets. Chapter 4 also discusses the spectrum broker realization solution and presents the implementation of spectrum broker market using LTE virtualization approach. In addition, important investigation of equilibrium characteristics in the modeled interaction is also the part of the chapter. Considering the network / service providers as the key players in the telecommunication value chain model (the importance of these providers is evident from their positions in the telecommunication value chain model i.e., they sit at the intersection of low and upstream markets). We investigate the settings where operators on inter-operators and intra-operator level optimize their objective functions in Chapter 5 & 6 respectively. The focus of these chapters remained on modeling the cooperative approaches and investigating the gains of proposed cooperative approaches against the existing approaches. Having highlighted all the dynamics in the system, one may be convinced that the dynamics of future wireless system will involve not only the time dependencies and the state of the environment but also the variability of the demands, the uncertainty of the system parameters, the random activity of the users, the time delays, error and noise in the measurement over long-run interactions, etc. To model such dynamic interactions, we chose learning and adaptive procedures that do not require any information about the other players i.e., we focus on hybrid and combined strategic learning for general-sum stochastic dynamic games with incomplete information and action-independent state transition in Chapter 8. Envisioning the telecommunication landscape and the evolving business models, we also discuss the coalition network selection ideas in Chapter 9, where we constitute the fundamentals of evolutionary coalitional games as well as their potential applications in wireless networking and communications in general, and coalition network selection in special. The contributed algorithms and interaction models with the underlying proposed architectural solutions are evaluated through simulations using OPNET Modeler and through subjective measurements, the details of simulation environment implementation can be found in Appendix A.

In future, we aim to extend the framework to coalitional hierarchical population games with different types of users. Owing to the fact that imperfectness and time delays are frequent in wireless networks and the measurements can be noisy and outdated, we will extend the framework to robust coalition network selection games and evolutionary coalitional games with incomplete information. We also aim at extending the modeling to multiple objectives, leading multiple objective evolutionary coalitional network selection games. The learning based user-centric network selection framework will be realized through mobile agents in the testbed environment i.e., WLAN and LTE are integrated through a IP flat core network.

Appendix A

OPNET Simulation Implementation

A.1 OPNET Simulation Implementation

In this section, we provide the details of simulation implementation that we used for the proof of our proposed concepts.

A.1.1 An Overview of OPNET Simulator

Opnet is an event driven simulation, where an event is a request for a particular activity to occur at a certain time. OPNET is a event-driven. Time, in the simulation, advances when an event occurs. The OPNET simulation maintains a single global event list, and all the objects access a shared simulation time clock. Events are scheduled on the list in time order. The first event on the list is the head. An event has data associated with it, upon completion of the event is removed from the list. The event turns into an interrupt when it reaches the head of the event list and is delievered by the Simulation Kernel to the designated module. Data associated with the event can be obtained by the module when the interrupt occurs. Within OPNET certain modules, processes and queues can be selected to place initial interrupts on the event list. OPNET comprises of:

1. Subnets A subnetwork abstracts network components specified within it into a single object and represent identical constructs in an actual network,

2. Links Link objects model physical layer effects between nodes, such as delays, noise, etc.

3. Nodes These are basic building blocks of node models. Modules include processors, queues, transceivers, and generators.

4. Processor These are the primary general purpose building blocks of node models, and are fully programmable.

5. Queues offer all the functionality of processors, and can also buffer and manage a collection of data packets.

Each object has associated attributes, which can be configured that depicts the object behavior. Attributes may be dynamically changeable during simulation. Different attribute values allow objects of the same type to behave differently. An attribute value can be promoted, which means that attribute value is assigned at the higher hierarchical level. Communication protocols, algorithms, queuing disciplines, traffic generators, statistics collection mechanism are all described in the process models of OPNET. The simulation termination is dictated by factors including; i) the event is emptied, ii) simulation attribute duration expires, iii) a process calls for termination, using the kernel process, and iv) any fatal error occurs. For more details the readers are encouraged to read the OPNET tutorial.

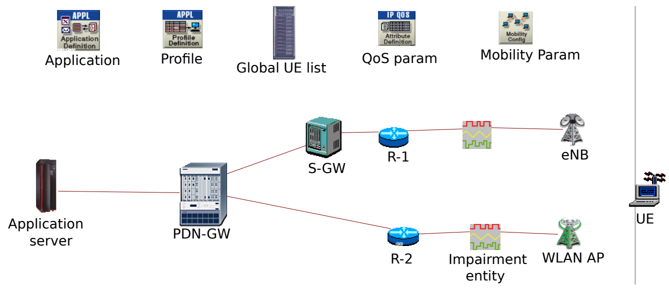


Figure A.1: OPNET simulation implementation of the scenario - The figure is the screen shot of the OPNET simulation setup, which is set up for analysis of the the simulation scenario

The basic reference architecture shown in Fig A.1 is implement using OPNET simulator environment. As can be viewed in the Fig A.1 that two access networks namely LTE and WLAN are connected to a common core network of the operator as per 3GPP recommendations for integration of 3GPP and non-3GPP access technologies (250). To have greater control of environment in terms of analysis, impairment entities are placed in the transport networks of each access technology. These entities introduce the controlled IP level impairments, e.g. packet delays, packet delay variations, and packet loss rate, etc., hence providing more control for experimentation, more details about this entity is provided later in this chapter. User terminal is multi-interface device, and capable of simultaneously connecting to multiple access technologies. In order to simulate the reference scenario presented in Fig A.1, the following entities are implemented:

1. User Equipment(UE),
2. e-Node-B (eNB),
3. Serving Gateway (S-GW),
4. Packet Data Network Gateway (PDN-GW),
5. Impairment Entity (IE),

whereas the following entities used in the simulation are OPNET standard node models:

1. Wireless LAN access point (wlan_ethernet_slip4_adv),
2. Application server (Ethernet_server_adv),
3. Ethernet link (1000BaseX_int),
4. Routers (ethernet8_router),
5. Mobility model (Mobility Config).

A.1.2 UE Node Model Implementation

The scenario provisions multi-interface terminal, which enables users to be associated with both WLAN and LTE. Fig A.2 shows the protocol stack for development of such a UE node, it further indicates the respective protocols of each interface, e.g. PDCP, RLC, MAC, and PHY layers for LTE interface, and LLC, MAC, PHY for WLAN interface. This dictates that implementing these protocol functionalities is necessary to have the required UE node. All the LTE protocols are implemented following 3GPP specifications. The transmission between the UE and eNB entities is modeled on the following lines:

- To better understand the procedure in the uplink, let us assume that UE receives the grant for transmission in the uplink from eNB MAC scheduler. Upon reception of the grant UE MAC scheduler computes the effective[1] SINR value and consults the AWGN Block Error Rate (BLER) curves to determine feasible Modulation Coding Scheme (MCS) for the target Bit Error Rate (BER). As soon as the MCS value is known, 3GPP tables (252) are consulted to figure out the Transport Block Size (TBS), now that TBS is known the MAC layer requests a RLC PDU of corresponding to TBS size. RLC then creates a PDU of required size by concatenating[2] or segmenting PDCP PDUs. RLC PDUs are the handed over to MAC layer and subsequently to PHY layer for further transmission to eNB. It should be noted here that PHY layer modeling is not included in the scope of this implementation, and its scope is only to tele-port the frames received from MAC to PHY layer of eNB.

- On downlink, the data received on the physical layer is forwarded to MAC, which upon reception of the data processes the frame headers and forwards the frames to RLC layer. RLC then de-capsulates PDUs and performs the re-assembly (in case of segmented PDCP PDUs) and re-ordering to ensure the in-sequence delivery of downlink data to PDCP layer. PDCP further de-capsulates the received PDUs and forward packets to IP layer.

The transmission between UE and WLAN access point is handled by the WLAN standards modeled in OPNET inherent model libraries, and readers are encouraged to refer the OPNET documentation for details, however for a reference the snap-shot of WLAN model attributes is given in Fig A.3. In addition to LTE and WLAN related protocol stacks shown in Fig A.4, one can notice the presence of another process model called flow_manager.

As evident from the figure that data from/to both the interfaces converge to the flow_manager, this highlights the importance of the process model and provisions the detailed functionality of it. The flow_manager entity in Fig A.4 takes care of splitting and managing the flow according to defined policies or any scholarly proposed algorithm. Upon implementation of algorithm

[1]Effective SINR value of all allocated PRBs is calculated using effective exponential SINR mapping (251).

[2]Concatenation is carried out in situations, where the data from multiple PDCP PDUs are packed into one RLC PDU, whereas on the contrary segmentation process bifurcates the bigger PDCP PDU into smaller size that fits RLC PDU size.

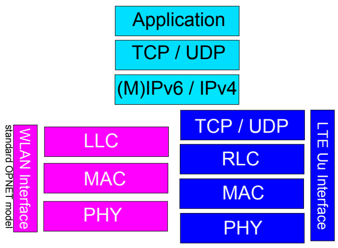
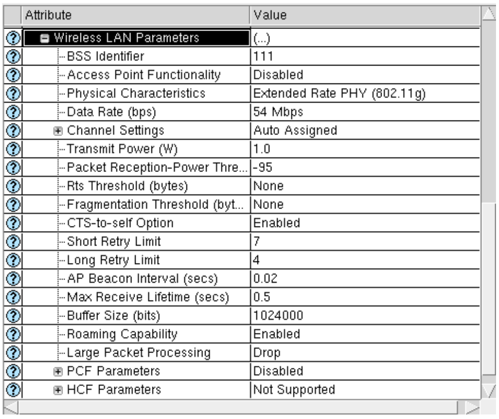


Figure A.2: Protocol Stack in UE Node Model - The figure shows the protocol stack of the UE node model, the figure also highltights the interfaces on both the sides.



Attribute	Value
Wireless LAN Parameters	(...)
BSS Identifier	111
Access Point Functionality	Disabled
Physical Characteristics	Extended Rate PHY (802.11g)
Data Rate (bps)	54 Mbps
Channel Settings	Auto Assigned
Transmit Power (W)	1.0
Packet Reception-Power Thre...	-95
Rts Threshold (bytes)	None
Fragmentation Threshold (byt...	None
CTS-to-self Option	Enabled
Short Retry Limit	7
Long Retry Limit	4
AP Beacon Interval (secs)	0.02
Max Receive Lifetime (secs)	0.5
Buffer Size (bits)	1024000
Roaming Capability	Enabled
Large Packet Processing	Drop
PCF Parameters	Disabled
HCF Parameters	Not Supported

Figure A.3: Snap shot of WLAN model attribute in OPNET - Figure shows various attributes of WLAN model, which can be customized by the users

Node Model: LTE_UE_multiIfc

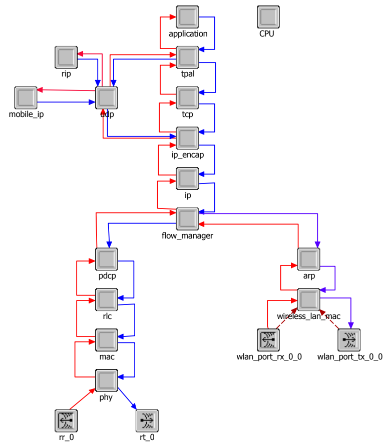


Figure A.4: Layered hierarchy of UE node model - Figure shows node model of with our proposed flow manager node implementation

in this entity, flow splitting, flow blocking, and flow steering can be performed as per requirements, and behavior / efficiency of the system may be analyzed. Fig A.5 represents the process model view of the flow_manager process model entity.

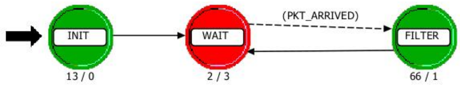


Figure A.5: Process model view of flow management entity - Figure represents the process model of the proposed flow management node model

Now that reader is familiar with the necessary knowledge about the protocol stack functionalities and UE basic correlation with eNB, it is the time to introduce the flow chart view[1] of these functionalities, which are followed for UE node model implementation. To further detail the procedures of UE node model, we make use of flow charts. A UE either receives data from eNB (downlink), or send data to eNB (uplink).

[1]Flow chart view focuses on the functionalities above L2, however the details of lower layers are already given in the start of this section.

- In the downlink, the packets received from either interfaces (LTE or WLAN) at flow_manager process model, and are simply relayed to IP layer. At IP layer the packets are decapsulated and further forwarded to upper layers until they reach the application layer. This is illustrated by the Fig A.6.

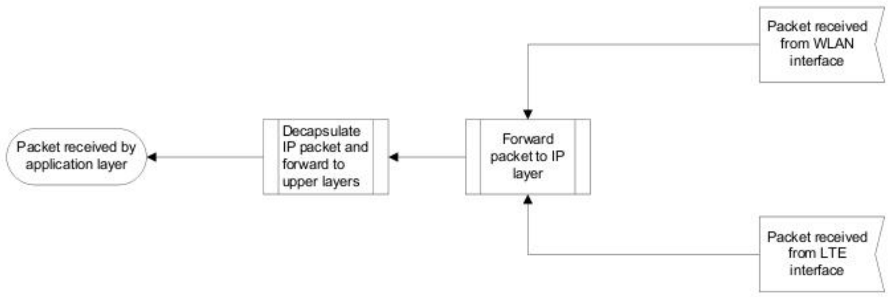


Figure A.6: Flow chart explaining the node procedure in case of downlink data - Figure represents the flow charts in case of downlink data

- In the uplink, the packets received from the application layer, processed in the UDP / TCP layer and forwarded to IP layer. Since the IP layer implements MIPv6, therefore, the received IP packets tunneled to HA address using IPv6 encapsulation mechanism. As can be seen from the Fig A.4 the IP packet leaving the IP process model enters the flow_manager process model entity, where the packet filtering takes place (as explained earlier). The flow_manager process model decides over interface selection for forwarding the packets to either LTE or WLAN access networks.
  - In case packets are to be forwarded to WLAN interface, the availability of WLAN network is checked. Packets are forwarded to WLAN only if the WLAN network is available, else they are forwarded to LTE network.
  - In case packet are to be forwarded to LTE network, on the similar lines as for WLAN, the availability of LTE network is checked and packets are forwarded to LTE only if it is available, otherwise they are forwarded to WLAN.

Intuitively, when none of the networks is available, the packets are dropped. This process is illustrated in flow chart given in Fig A.7.

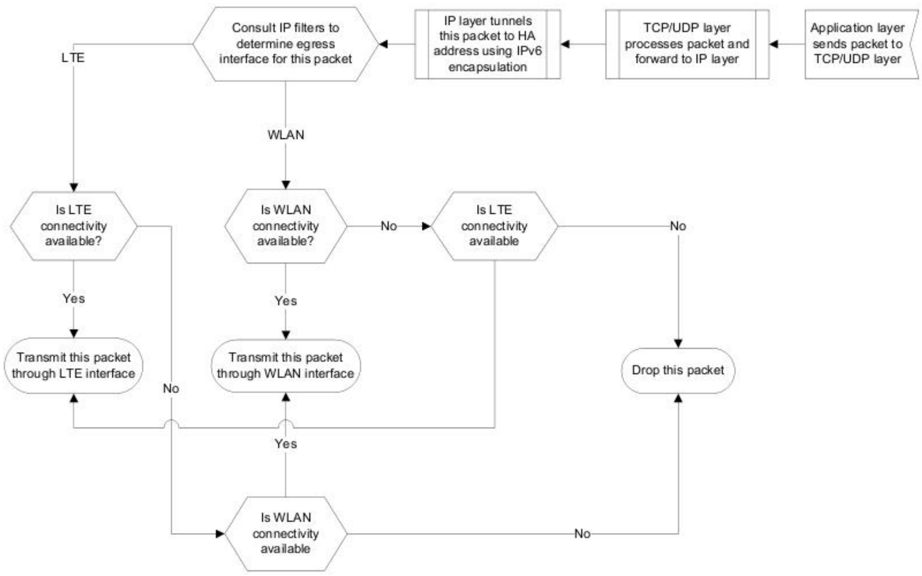


Figure A.7: Flow chart explaining the node procedure in case of uplink data - Figure representing the flow chart representing the procedure node procedure in the uplink data

Remark 18. *The behavior of network selection in situations, when the preferred network is unavailable may be modified e.g., if the preferred network interface is unavailable, then the packets may be dropped instead selecting the alternate access network. Its worth mentioning how the UE maintains network availability information. The network availability update process is carried out by periodically updating UE's context information. However to keep things simple, here UE measures its distance from either of the access point / eNB. Technology availability flag is set or reset based on its distance measurements from the eNB or access point and the configured network coverage. This process is illustrated in Fig A.8.*

A.1.3 eNodeB Node-model Implementation

As per 3GPP specifications, eNB has two interfaces namely Uu and S1 interface, Uu interface is responsible for providing the radio access to UEs and S1 interface transports the data to/from serving gateway (S-GW) via transport network. Fig A.9 shows the eNB node model respective protocol layers. The details of interface functionalities are as follows:

- Uu interface This interface includes the following four protocol entities:
  - **PDCP** The simplified version of user plan protocol layer of PDCP is implemented

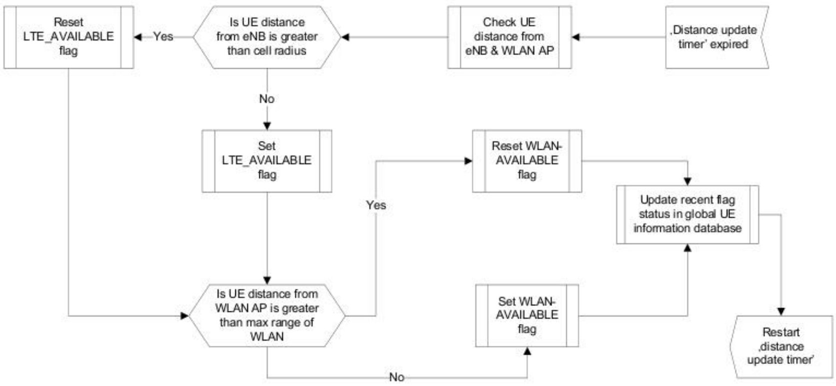


Figure A.8: Flow chart explaining the node distance time update process - ..

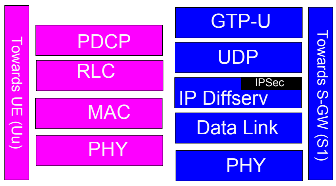


Figure A.9: Layered hierarchy and protocol stack of eNB node-model - details

as per 3GPP specifications (253, 254). PDCP is mainly responsible for; i) maintains the list of active bearers, ii) allocates the buffer space for each bearer of the active bearer list, iii) identifying the bearer associated with the incoming packet and buffering them in to their respective queues, iv) carries out the buffer management following buffer management techniques, such as RED, WRED, or simple tail-drop, etc., v) performs the encapsulation and de-capsulation of PDCP PDUs.

- **RLC** This protocol layer performs in exact similar fashion as explained in sectionA.1.2, therefore the details are left away here.
- **MAC** - This protocol layer encampuses the resource scheduling functionalities. Air interface being the resource is scheduled amongst the users in both uplink and downlink by the MAC schedulers. Owing to the fact that OFDM technology is used in LTE, the scheduler effectively distributes the radio resources in both time and frequency domains. The smallest scheduling resources unit is called Physical Resource Block (PRB). LTE MAC scheduling is carried out by schedulers at two different stages, these schedulers are known as Time Domain (TD) and Frequency

QCI to MAC QoS class mapping		
Bearer Type	Service type (QCI)	MAC QoS Class
GBR	QCI 1	M-QoS1
Non-GBR	QCI 8	M-QoS2
	QCI 9	M-QoS 3

Domain (FD). The TD scheduler is used to differentiate the users according to their QoS characteristics, whereas the FD scheduler is responsible for assigning the radio resource between the between the priority users. The MAC scheduler considers two main types of QoS bearers: Guaranteed Bit Rate (GBR) and Non Guaranteed Bit Rate (non-GBR). Based on the QoS Class Identifier (QCI), the incoming packets are categorized with respect to their priority order (see the Table below) into three different MAC QoS classes that are defined by the MAC scheduler.

The highest MAC QoS class (QCI 1) represent the GBR bearers, whereas the other three represent the non-GBR bearers. The MAC scheduler performs strict priority scheduling for all GBR bearers (i.e., served first) and then scheduling the non-GBR bearers.

A.1.4 Time-Domain (TD) Scheduler

The TD scheduler creates two candidate lists (one for GBR and the other for non-GBR). The GBR candidate list is created by adding all bearers in MAC-QoS1 class in the top of the candidate list and then adding the MAC-QoS2 class bearers. As for the non-GBR bearer list, the TD scheduler adds the entire non-GBR MAC-QoS class bearers into the candidate list and then prioritizes them based on their priority factor. The priority factor is calculated as follows:

$$P_f = \frac{MQoS}{R_{occur}} \tag{A.1}$$

and

$$P_f = \frac{MQoS_{weight}}{R_{avg}} \tag{A.2}$$

where P_{f0} is the priority factor at iteration 0, QoSweight is the weight of the MAC QoS class, and R_{avg} is the average data rate of that bearer from the past. R_{avg} can be calculated as follows:

$$R_{avg}(n)\alpha R_{avg}(n-1)+(1-\alpha)R_{inst} \tag{A.3}$$

Where $R_{avg}(n)$ is the average bearer data rate at the n_{th} TTI, α is the smoothing factor, and R_{inst} is the instantaneous bearer data rate at n_{th} TTI.

A.1.5 Frequency-Domain (FD) Scheduler

The FD scheduler starts with the GBR candidate list provided by the TD scheduler. The PRBs allocation is done iteratively, where in each iteration one PRB that has the highest SINR value is allocated for one bearer. The bearers in the candidate list get orderly (based on their priority) a chance to select the next best PRB from all the available PRBs upon the highest SINR value, this PRB allocation process continues until all bearers in candidate list get one PRB. At the end of each iteration the achieved data rate of each bearer is calculated and checked if sufficient data is available in the bearer buffer to be served or if the sufficient guaranteed rate is achieved for that particular bearer. In case, one of the above conditions is satisfied, the bearer is removed from the candidate list and scheduled. Otherwise, the bearer is kept in the candidate list for the next iteration. The data rate for each bearer is calculated through the allocated PRBs SINRs, where the effective SINR value of all the allocated PRB(s) can be calculated by using the Effective Exponential SINR Mapping (EESM) (255). Then it is compared against the target SINR value that is calculated from the Additive White Gaussian Noise (AWGN) Block Error Rate (BLER) curves (by setting a target BLER value e.g. 10%). If the effective SINR is lower than the target one, then the Modulation and Coding Scheme (MCS) is lowered, and the effective SINR is recalculated. Otherwise, using the 3GPP tables defined in [8], the Transport Block Size (TBS) is determined and it represents the data rate of the bearer for this TTI. Once all GBR bearers are scheduled, the FD scheduler starts scheduling the non-GBR bearers. The FD scheduler picks the highest N non-GBR bearers from the non-GBR candidate list to be served this TTI. The same iterative procedure used in the GBR scheduling is also used here with one exception: after each iteration the non-GBR bearers are re-prioritized using the newly calculated priority factor as given below:

$$P_{fj}=(P_{fj}-1)TBS_j \tag{A.4}$$

Where P_{fj} is the priority factor at the jth iteration, TBS_j is the transport block size at the jth iteration. The reason why the re-prioritization of the non-GBR bearers is done between the iterations is mainly to provide more chances to the non-GBR bearer who has better channel conditions compared to others to select its best PRBs first.

A.1.6 Channel Modeling

The channel model includes the well known factors: path loss, slow fading and fast fading. By using the link budget the different Signal to Interference plus Noise Ratio (SINR) per each Physical Resource Block (PRB) is calculated for each connection. This represents the user channel conditions that differ between the different PRBs due to the frequency and time selectivity. The path loss is calculated as follows:

$$L = 128.1 + 37.6Log10d \tag{A.5}$$

The slow fading is typically modeled using a log normal distribution with zero mean and a variance, but the time correlation between the slow fading values needs to be considered. For such a model, consider a moving mobile user starting at an initial point P where the slow fading value is to be randomly generated using the log-normal distribution equal to S (0). The shadowing at points which are at distance δ, 2δ, 3δ away from P, can be determined according to (252) as follows:

$$S(n\delta) = e^{-\frac{\delta}{X_c}} S((n-1)\delta) + V_i \tag{A.6}$$

where the V_i are independent and identically distributed normal random variables with zero mean, and a variance $\sigma_2^2 = \sigma^2[1 - e(\frac{-2\delta}{X_c})]$ in dB. X_c is the de-correlation distance. As for the fast fading, the implementation of the ChSim [8] is used to model the Doppler spread for the time selectivity and the delay spread for frequency selectivity.

PHY The modeling of PHY layer is out of the scope of implementation setup, therefore it is only responsible for tele-porting the frames received from MAC layer to UE physical layer.

- S1 interface - This interface includes the following protocol entities:

- GTP - The simplified version of user plan protocol layer of GTPv1 is implemented as per 3GPP specifications (253, 254). GTP creates the transport tunnel over the UDP protocol between eNB and S-GW. On the uplink, the IP packets from PDCP process model are encapsulated in GTP packet format, which are further handed over to UDP. At UDP layer the GTP packet is taken as the payload of the UDP datagram, which is then forwarded to IP layer. IP packets are then forwarded over the transport network to the S-GW. On the downlink, GTP receives the GTP encapsulated packets from UDP layer. After processing the GTP headers, the de-capsulated IP packets are forwarded to PDCP layer.
- UDP The simulation includes standard OPNET model that forwards datagrams to GTP layer with a specified port number.
- IP The simulation includes standard OPNET model that transmit IPv4 and IPv6 formatted packets.
- L2, and L1 layers are standard OPNET model that perform the Ethernet related functions.

An important point here to notice is the block highlighting the eTPS node. eTPS is the node where diffServ model can be implemented, which may further include traffic differentiation and scheduling in the IP layer as well as shaping functionalities at the Ethernet layer in the uplink. The eTPS schedules is specific to uplink and addresses the potential bottleneck last mile link.

A.1.7 Serving gateway (S-GW) Node Model Implementation

S-GW is a logical entity. Fig A.10 depicts the user plane transport protocols and Fig A.11 represents the S-GW node model view. S-GW has two interfaces namely S1, that connects the S-GW to eNB, whereas on the other interface, S5 connects S-GW to PDN-GW. S5 interface is used in non-roaming scenarios, where the S-GW is located in the home network. S-GW provides on both sides peer to peer transport protocol, i.e. GTP, UDP, IP, and Ethernet, which are located towards the transport network. It should also be noted that the S-GW serves as a termination point for two GTP tunnels; one from eNB and the other from PDN-GW. S-GW is mainly responsible for creation, deletion, modification, change of bearers for individual users connected to EPS, these functions are performed on a per PDN connection for each UE. The

S-GW provides the local anchor functionality for a single terminal for all of its bearers and manages them towards PDN-GW. In addition to the functionalities discussed in the previous paragraph, S-GW also takes care of routing uplink traffic from eNB to the PDN-GW, and downlink traffic from PDN-GW to eNB using the GTP tunnels. The traffic routing procedure details are presented in the figure, which says that the source IP address is checked after GTP packet decapsulation, if the source address is that of eNB, the S-GW assumes that the packet has to be GTP encapsulated and forwarded to PDN-GW and vice versa.

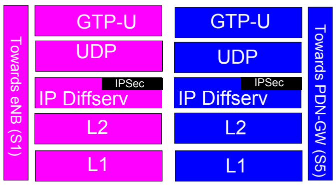


Figure A.10: Protocol stack in S-GW model - Figure representing the protocol stack of S-GW

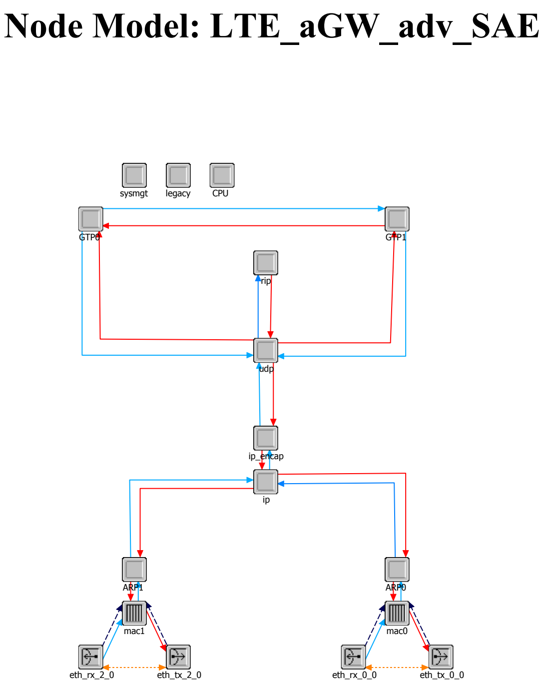


Figure A.11: Service gate-way node model view - Figure representing the nodal details of S-GW

A.1.8 Packet Data Network Gateway (PDN-GW) Implementation

PDN-GW is a logical entity, Fig A.15 depicts the user plane transport protocols of PDN-GW. It is a central entity for connecting the external IP networks through SGi[1] interface, all 3GPP networks through S5[2] and non-3GPP networks through interface S2c[3], within the scope of this implementation the trusted non-3GPP network with host-based mobility solution is considered. As evident from the figure that other than the mentioned three interfaces, there exists a fourth interface, which is basically assumed to be associated with the home link of UE. As the UE is always associated with either eNB or WLAN and is never associated with its home link, therefore it can be assumed that UE is always in foreign network.

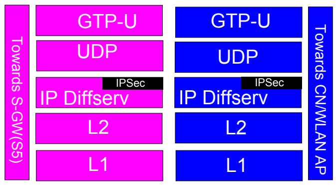


Figure A.12: Protocol stack in PDN-GW model - Figure representing the protocol stack of PDN-GW

The details of PDN-GW functionalities are given can be found in the literature. In order to understand the functionalities PDN, lets consider a scenario, where a UE is mobile and its current point of attachment is a foreign network. The foreign networks may either be WLAN or LTE. Assume that the Correspondent Node (CN) in this scenario is an application server i.e., a mobile UE communicates with application server on the move. In the considered network integration architecture, the PDN-GW takes the role of HA. Lets now consider the following two cases:

- When a mobile UE is in WLAN foreign network In uplink the UE tunnels its traffic using IPv6 encapsulation and forwards to its HA(PDN-GW). Upon receiving the IPv6 encapsulated packets, the HA decapsulate them and routes them towards the application server (CN). In downlink the CN sends the traffic UEs home address, which is intercepted by the UE HA. HA then encapsulates the traffic using IPv6 encapsulation and route it to the UE over S2c interface.

[1]SGi interface is based on the standard OSI protocol stack
[2]S5 interface utilizes the GTP protocol over UDP / IP
[3]S2c interface implements IP over Ethernet

Node Model: PDN_GW

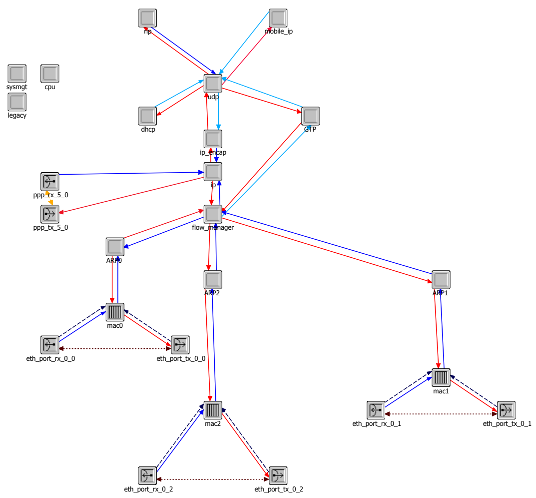


Figure A.13: Layered hierarchy of PDN-GW node-model - ..

- When a mobile UE is in LTE foreign network In uplink the UE tunnels its traffic using IPv6 encapsulation and transmit it via Uu interface to eNB. eNB then forwards UE received traffic via GTP tunnel to S-GW. The S-GW then sends the packets to PDN-GW through another GTP tunnel that exists between S-GW and PDN-GW. The decapsulation of packets at PDN-GW consequences in IPv6 encapsulated packets, which were basically encapsulated by UE. Intuitively the CN is taken as the termination point of these encapsulated packets, therefore PDN-GW further decapsulates the IPv6 encapsulated packets and forwards the original packets to CN. In downlink the CN sends the UE traffic at UEs home address. Upon reception of these packets at UE home network, they are intercepted by UE HA (PDN-GW), HA then encapsulates this traffic using IPv6 encapsulation and forwards it over S5 interface, this dictates that a further GTP tunneling at PDN-GW is required owing to the fact that there exists a GTP tunnel between PDN-GW and S-GW. S-GW now decapsulates the received packets and in order to send these packets over another GTP tunnel between S-GW and eNB, S-GW encapsulates the packets using GTP tunneling protocol. Upon reception at eNB, the packets are decapsulated, which result in IPv6 encapsulated packets. These IPv6 encapsulated packets are then transmitted over the Uu interface to UE, where the decapsulated and forwarded to application layer.

** When packets are forwarded to FM entity - The flow_manager process model acts a relay to the IP process model in the uplink, whereas in the downlink it applies the filter rules over the traffic, e.g. upon reception of the packets at the flow_manager process model from the IP layer, then the flow-splitting algorithm(s) are executed and the decision over further forwarding the packets to either WLAN or LTE is taken, otherwise the packets are relayed to corresponding L2 interface. Intuitively the consequence of flow splitting algorithm is either WLAN or LTE, this discern two branches of further implementation as follows:

- If the packet is forwarded to WLAN in this case the packets are directly forwarded to S2c interface, if the UE is within the coverage of WLAN network.

- If the packet is forwarded to LTE The packets are sent to GTP/UDP layer for GTP encapsulation and the forwarded over the S5 interface.

A typical policy dictates that UE packets are forwarded to an alternate network if the preferred network is not available to UE, and dropped in case none of the access networks are available. However these decisions are strictly operator driven and case dependent. The flow charts given in Figure: A.16,A.17, A.18 present implemented details of PDN-GW operation.

In order to provide MCoA support OPNET provided implementation of MIPv6, found mainly in library C file ”mipv6_signaling_sup.ex.c”, has been extended. MCOA is then further extended to provide flow management functionality. After these extensions UE is capable of connecting and registering its WLAN and LTE access networks simultaneously by sending biding update message accroding MCoA specification. HA is capable of processing binding update messages sent by UE. Moreover UE can also send flow bindings to HA in order to install filters at flow_manager entity and hence perform flow management.

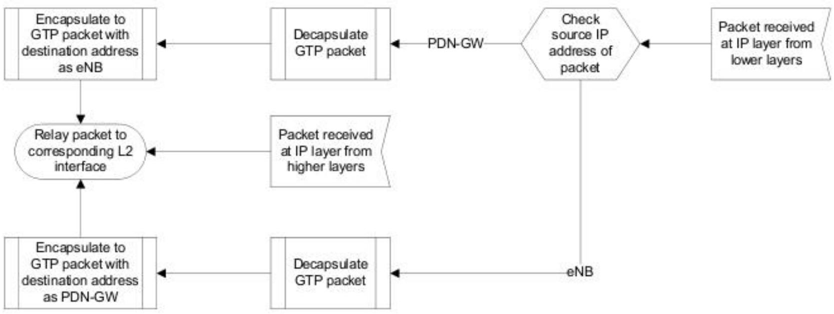


Figure A.14: Flow chart explaining the details of PDN-GW node model functionalities this is the modified figure - details

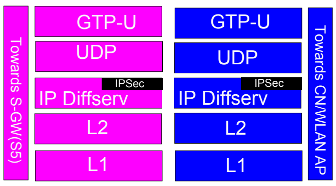


Figure A.15: Protocol stack in PDN-GW model - Figure representing the protocol stack of PDN-GW

A.1.9 Impairment Entity Implementation

In order to model the behavior of IP impairments in the LTE / WLAN transport network, and impairment injecting entity is simulated using OPNET simulator. This entity can impose certain packet delays, packet delay variation as well packet losses according to pre-defined impairment profiles on all packets flowing through the transport link. For generating packet

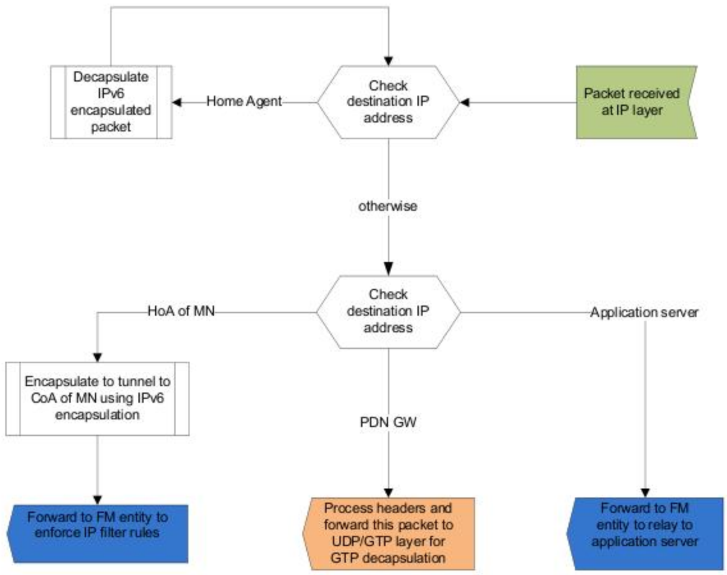


Figure A.16: Flow chart explaining the details of PDN-GW node model functionalities - ..

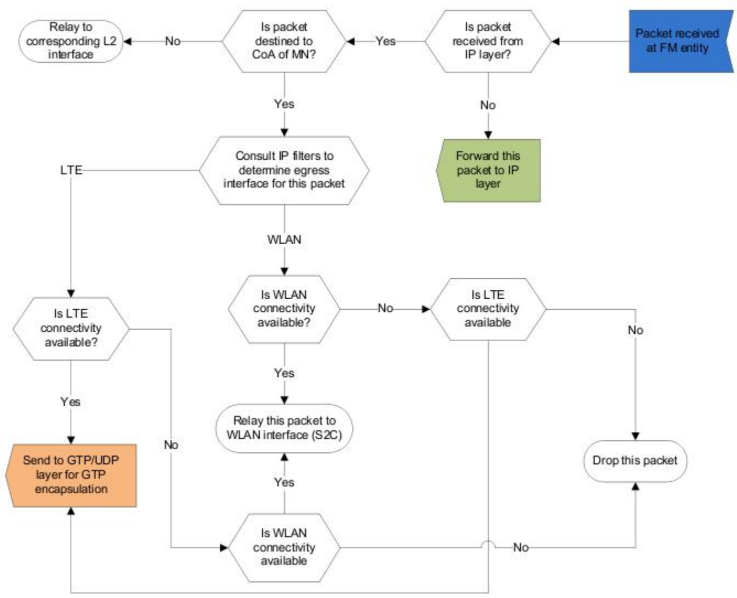


Figure A.17: Flow chart explaining the details of PDN-GW node model functionalities - ..

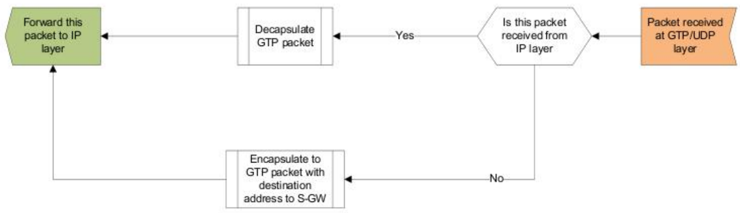


Figure A.18: Flow chart explaining the details of PDN-GW node model functionalities - ..

delays and delay variations the probability density functions and associated parameters (e.g. standard deviation, mean, etc.) need to be given as input for impairment injecting entity. For generating packet losses, a single packet loss ratio is specified. Packet losses introduced in IP packet stream are uniformly distributed. Fig A.19 presents the node model view of the impairment entity.

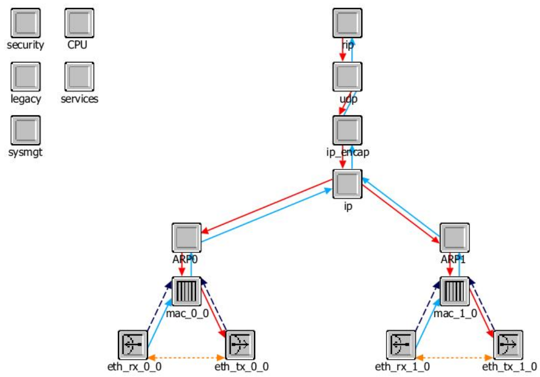


Figure A.19: The node model view of impairment entity - Figure representing the nodal details of impairment entity

The crux of the procedure is highlighted in the flow chart given in Fig A.20.

A.2 Results of the Scenario Run on Implemented Simulation setup

With the view to ensuring the proper working of the simulation, we implemented the following simplified scenario.

The case scenario dictates that an operator owns two access technologies namely LTE and WLAN in a geographical coverage area. The operator is enabled to extend heterogeneous services to the users via both the access technologies. A user may be connected to the ap-

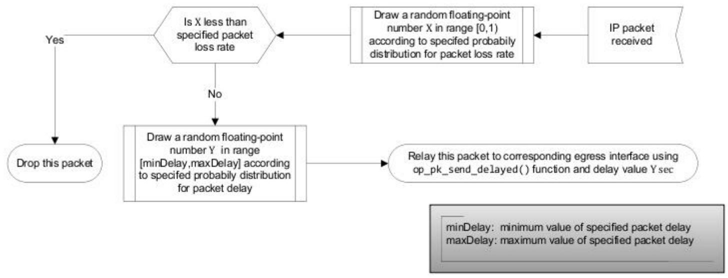


Figure A.20: Flow chart presenting the details of impairment entity node model - details

plication server for an application via both the access network interfaces simultaneously, or on two different interfaces for two different applications. Owing to the wireless medium in the access network, users experience quality degradation. The user (in case of simultaneous interfaces connectivity per application) may switch the interfaces during the life-time of the call, similarly user applications (in case of one application per interface) may be switched between the two interfaces, these switching over decisions are driven by different factors, which may include change in user-preferences, user-context, application requirements, etc. Although the scope of the scenario is limited to a single operator, which does not explicitly analyze the inter- operator handover, the scenario is flexible enough to infer the effects of handovers among network operators for simultaneous interface utilization. The simulation setup focuses on the solution considering the integration of host based access with trusted 3GPP network. Assume that Alice has contractual agreement for heterogeneous services (video and FTP) with operator-A, the operator-A has deployed LTE and WLAN access technologies, which are connected to the common core network of the operator. Although mobile Alice is under the overlapping coverage of both LTE and WLAN access technologies. Alice at different time instances use two simultaneous interfaces for both video and FTP applications, however the preferences over the interface usage is dynamic and depends on her mood, time of the day, service charges or service quality. She has the option to use one interface per application, or multiple interfaces per application meaning thereby both the applications run simultaneously on both the interfaces.

The implemented simulation can be useful in various research directions including mobility management (vertical / horizontal handovers, handover delays, packet loss, etc.), load balancing (effects of congestion on the transport network, routing traffic on alternate paths, etc.), efficiency introduced by traffic splitting, user-centric network selection, etc. However for very minute modification or attribute settings in the implemented simulation setup are needed to analyze the desired scenario.

A.2.1 Case-study 1: User-Centric Network Selection

As a first case study we analyze a simple user-centric network selection scenario in the context of scenario described above. The simulation settings for this simple scenario say that Alice aggregated request for both services is 600kbps where 300kbps are counted for video service and 300kbps are counted for FTP. Maximum bandwidth available to FTP connection is controlled by performing shaping at IP layer of UE. Homogeneous quantity of traffic demands has been considered for the sake of simplicity.

At the start of simulation UE has only LTE interface available. UE attaches to LTE network, gets an IP address which is actually a CoA. Afterwards it registers its first CoA with HA. A moment after this operation UE detects WLAN hotspot coverage. UE attaches to the WLAN network and obtains another IP address which is its second CoA. Thanks to MCoA implementation, this allows UE to register its second CoA with HA. After successful completion of this operation UE has two network access interfaces available however LTE is configured as default interface by sending a flow binding update.

At first time instance (300 sec in results show in Fig A.21), Alice starts two services simultaneously. Data streams of both services reach UE through LTE because it is the default interface. However, just a moment later due to cheaper WLAN access availability UE prefers shifting the FTP traffic to WLAN. This triggers a flow binding update message carrying a filter rule which is received and installed at flow manager entity inside home agent. The result of this operation is visible in Fig A.21 where 300kbps of data traffic are steered towards WLAN. And therefore FTP data stream takes its path to UE through WLAN while Video is still being forwarded through the default LTE network. Few moments later around busy hour calls the 3GPP connection, i.e. LTE is least preferred by Alice and all the traffic is transferred to WLAN. This decision of Alice again triggers the transmission of a flow binding message by UE. This flow binding update message carries a new filter rule which overrides previous filter rule. According to new filter rule WLAN shall be considered as default interface for all user traffic. After installing this filter rule now flow manager entity steers both FTP and Video traffic to WLAN interface. This effect is visible at simulation time instance 600 sec.

Although very simple scenarios run on the simulation, the objective is to evaluate the correct functionalities implementation of simulator. As can be seen that the results advocate that flow splitting functionality, handover functionality, and simultaneous connectivity functionality are accurately implemented. Flipping this scenario by activating the network-based mobility solution will provide excellent evaluation platform for operator resource allocation problems.

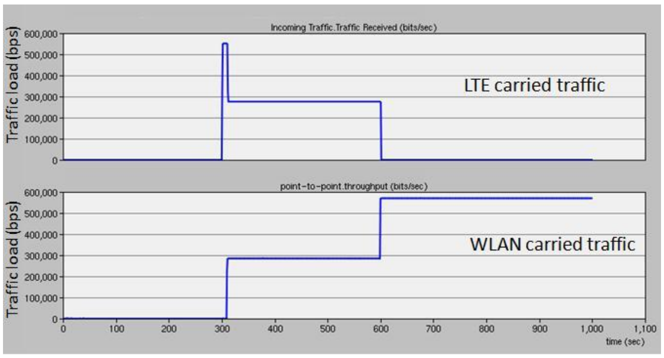


Figure A.21: Simulation results of flow splitting for the considered simulation scenario - Figure details the curves resulted from the simulation runs in terms of gain attained from splitting

In this case study we will analyze the effects of IP transport network impairments on user QoE by our simulation environment. Impairments are introduced using IP impairment entity and the results obtained from OPNET simulator are used to evaluate VoIP call quality. OPNET has builtin functionality for VoIP call quality evaluation using modified E-model (256). We have analyzed Mean Opinion Score (MOS) (257) values of uncompressed voice codec G.711 (258) against different values of packet loss and packet delay. G.711 was chosen because it is lossless codec and therefore it can be considered as a benchmark for other lossy codec like G.729A (259), GSM EFR (260), etc. which are mostly used in IP networks to save network bandwidth.

In order to make the scenario simple only one user is considered in LTE system that is making a voice call using G.711 codec with data rate 96kbps. There is no user in WLAN network and user handover from LTE to WLAN network is disabled. LTE Transport network and Uu interface has sufficient bandwidth to carry this call and hence there is no congestion at any point in the system. Therefore it can be safely assumed that major component of VoIP packet end-to-end delay and loss will come from impairment entity.

Fig A.22 shows interface for setting attributes values of impairment entity. The impairment entity influence both downlink (IF0) and uplink (IF1) traffic. Impairment packet delay can be defined as either a constant value or probability distribution. Moreover a probability distribution can also be truncated or time shifted using Max packet delay, Min packet delay and Time

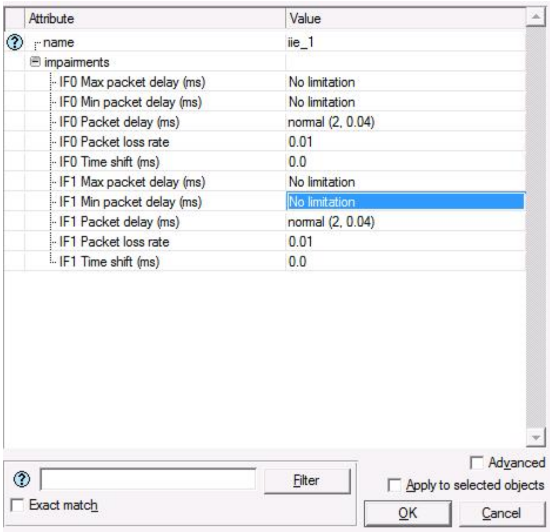


Figure A.22: Interface for setting attribute values of impairment entity - ..

shift values. However packet loss rate is defined as a probability of packet loss following uniform distribution. In current scenario packet loss rate is changed from 0% to 3% and packet impairment delay is changed from 0 ms to 300 ms. Packet impairment delay follows normal distribution. Other parameters to modify packet impairment delay distribution like Max packet delay, Min packet delay and Time shift remain unaffected.

User profile has been configured in a way that he makes VoIP call of length 90 sec and time between end of a call and start of next call is negative exponentially distributed with mean 10 s. Simulation is run for 3000 sec of simulation time and repeated for 3 different seed values. Average value of MOS from each scenario with a particular packet impairment delay and packet loss rate value is collected. Afterwards another mean MOS value is obtained by taking average of MOS values for three simulations run with different seed values. Fig A.23 is the final figure of average MOS values against packet impairment delay and packet loss rate(PLR).

A.3 Conclusion

This chapter extensively details the simulation setup that may be used an evaluation framework for broad range of future wireless communication scholarly approaches. It also gives the detailed back ground knowledge on the provisioned standards and approaches, thus facilitating

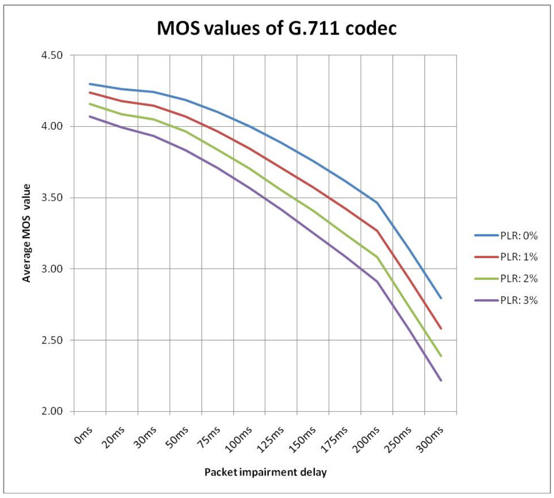


Figure A.23: MOS values of G.711 codec - Figure details the MOS values of G.711 codec for different packet impairment delay and packet loss rate values

readers with basic knowledge and guiding them to evaluate their ideas on a well know network simulation framework.

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