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Flexible Cross Layer Optimization for Fixed and Mobile Broadband Telecommunication Networks and Beyond

- Engineering Doctorate Dissertation -

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Flexible Cross Layer Optimization for Fixed and Mobile Broadband Telecommunication Networks and Beyond

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Abstract

As the telecommunication world moves towards a data-only network environment, signaling, voice and other data are similarly transported as Internet Protocol packets. New requirements, challenges and opportunities are bound to this transition and influence telecommunication architectures accordingly. In this time in which the Internet in general, and telecommunication networks in particular, have entered critical infrastructures and systems, it is of high importance to guarantee efficient and flexible data transport. A certain level of Quality-of-Service (QoS) for critical services is crucial even during overload situations in the access and core network, as these two are the bottlenecks in the network. However, the current telecommunication architecture is rigid and static, which offers very limited flexibility and adaptability.

Several concepts on clean slate as well as evolutionary approaches have been proposed and defined in order to cope with these new challenges and requirements. One of these approaches is the Cross Layer Optimization paradigm. This concept omits the strict separation and isolation of the Application-, Control- and Network-Layers as it enables interaction and fosters Cross Layer Optimization among them. One indicator underlying this trend is the programmability of network functions, which emerges clearly during the telecommunication network evolution towards the Future Internet. The concept is regarded as one solution for service control in future mobile core networks. However, no standardized approach for Cross Layer signaling nor optimizations in between the individual layers have been standardized at the time this thesis was written.

The main objective of this thesis is the design, implementation and evaluation of a Cross Layer Optimization concept on telecommunication networks. A major emphasis is given to the definition of a theoretical model and its practical realization through the implementation of a Cross Layer network resource optimization system for telecommunication systems. The key questions answered through this thesis are: in which way can the Cross Layer Optimization paradigm be applied on telecommunication networks; which new requirements arise; which of the required functionalities cannot be covered through existing solutions, what other conceptual approaches already exist and finally whether such a new concept is viable. The work presented in this thesis and its contributions can be summarized in four parts: First, a review of related work, a requirement analysis and a gap analysis were performed. Second, challenges, limitations, opportunities and design aspects for specifying an optimization model between application and network layer were formulated. Third, a conceptual model - Generic Adaptive Resource Control (GARC) - was specified and its prototypical implementation was realized. Fourth, the theoretical and practical thesis contributions was validated and evaluated.

Zusammenfassung

In der heutigen Zeit, in der das Internet im Allgemeinen und Telekommunikationsnetze im Speziellen kritische Infrastrukturen erreicht haben, entstehen hohe Anforderungen und neue Herausforderungen an den Datentransport in Hinsicht auf Effizienz und Flexibilität. Heutige Telekommunikationsnetze sind jedoch rigide und statisch konzipiert, was nur ein geringes Maß an Flexibilität und Anpassungsfähigkeit der Netze ermöglicht und darüber hinaus nur im begrenzten Maße die Wichtigkeit von Datenflüssen im wiederspiegelt.

Diverse Lösungsansätze zum kompletten Neuentwurf als auch zum evolutionären Konzept des Internet wurden ausgearbeitet und spezifiziert, um diese neuartigen Anforderungen und Herausforderungen adäquat zu adressieren. Einer dieser Ansätze ist das Cross Layer Optimierungs-Paradigma, welches eine bisher nicht mögliche direkte Kommunikation zwischen verteilten Funktionalitäten unterschiedlichen Typs ermöglicht, um ein höheres Maß an Dienstgüte zu erlangen. Ein wesentlicher Indikator, welcher die Relevanz dieses Ansatzes unterstreicht, zeichnet sich durch die Programmierbarkeit von Netzwerkfunktionalitäten aus, welche sich aus der Evolution von heutigen hin zu zukünftigen Netzen erkennen lässt. Dieses Konzept wird als ein vielversprechender Lösungsansatz für Kontrollmechanismen von Diensten in zukünftigen Kernnetzwerken erachtet. Dennoch existiert zur Zeit der Entstehung dieser Doktorarbeit kein Ansatz zur Cross Layer Optimierung in Festnetz-und Mobilfunknetze, welcher der geforderten Effizienz und Flexibilität gerecht wird.

Die übergeordnete Zielsetzung dieser Arbeit adressiert die Konzeptionierung, Entwicklung und Evaluierung eines Cross Layer Optimierungsansatzes für Telekommunikationsnetze. Einen wesentlichen Schwerpunkt dieser Arbeit stellt die Definition einer theoretischen Konzeptionierung und deren praktischer Realisierung eines Systems zur Cross Layer Optimierung für Telekommunikationsnetze dar. Die durch diese Doktorarbeit analysierten wissenschaftlichen Fragestellungen betreffen u.a. die Anwendbarkeit von Cross Layer Optimierungsansätzen auf Telekommunikationsnetzwerke; die Betrachtung neuartiger Anforderungen; existierende Konzepte, Ansätze und Lösungen; die Abdeckung neuer Funktionalitäten durch bereits existierende Lösungen; und letztendlich den erkennbaren Mehrwert des neu vorgeschlagenen Konzepts gegenüber den bestehenden Lösungen.

Die wissenschaftlichen Beiträge dieser Doktorarbeit lassen sich grob durch vier Säulen skizzieren: Erstens werden der Stand der Wissenschaft und Technik analysiert und bewertet, Anforderungen erhoben und eine Lückenanalyse vorgenommen. Zweitens werden Herausforderungen, Möglichkeiten, Limitierungen und Konzeptionierungsaspekte eines Modells zur Cross Layer Optimierung analysiert und evaluiert. Drittens wird ein konzeptionelles Modell - Generic Adaptive Resource Control (GARC) - spezifiziert, als Prototyp realisiert und ausgiebig validiert. Viertens werden theoretische und praktische Beiträge dieser Doktorarbeit vertiefend analysiert und bewertet.

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Chapter 1

Introduction

1.1 Motivation

Telecommunication Service Providers (TSP) and network operators are facing the challenge of massively increasing IP data traffic in general and Diameter signaling in particular within the operator core network, as discussed in various international telecommunication conferences nowadays. The decoupling of total data traffic amount from TSPs revenue streams threatens the business models of network operators worldwide. Starting from a pure voice call dominated circuit-switched area - in which operators gain revenues from subscribers fees, voice call minutes and short-messages - the transport network evolved towards an All-IP packet-switched network, which is challenged by high data traffic. Network operators need to balance their Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) smartly and in a positive ratio to the Average Revenue Per Subscriber (ARPU). Especially in the mobile telecommunication domain the TSPs expenditures are high, where network operators have to invest in redundant hardware equipment, antennas, cables, software, energy, maintenance, renting sites (locations for the antennas and base stations), regulatory spectrum license fees in addition to extra core network expenditures and other cost factors.

According to the white paper of CISCO [1], the increased IP data and Diameter signaling traffic is caused by the tremendously growing number of connected mobile devices on the market, numerous applications and bandwidth consuming multimedia streaming services and fast technology product cycles.

Access and core network congestion handling is a hot topic discussed at industry conferences [2, 3] and in standardization activities of the 3rd Generation Partnership Project (3GPP) especially in context of 3GPP Policy Control and Charging (PCC) [4]. In addition, three different 3GPP Feasibility Studies (FS) have been started to analyze impact on, challenges for and approaches for access and core network congestion handling [5, 6, 7]. All the existing approaches are limited to the network layer, without taking application requirements into consideration.

Since 2011 Fixed and Mobile network operators have been coping with network outage problems [8, 9] due to overload situations caused by the high amount of smart phone IP data traffic and signaling messages.

Even more devices will be entering the network through Machine Type Communication in the coming years. Over the past few years the Internet has entered further crucial economic domains such as eHealth, finance, public services, security, entertainment, tourism and evolved to a critical infrastructure.

From a technical viewpoint, the Internet consists of horizontal layers, each having a dedicated functionality. The International Organization for Standardization (ISO)/ Open Systems Interconnection (OSI) Reference Model aggregates functions of a similar type into individual layers, which are separated logically and physically from each other. All layers are accumulated and dedicated interfaces between adjacent layers allowing information exchange.

Nevertheless information exchange among these layers is limited. Therefore network-awareness for applications and application-aware networking are not supported. Such an isolation is caused by the software technical design goal for supporting the full substitution of a single layer without affecting the adjacent layers.

This missing direct control interface between application layer and network layer is addressed through the Cross Layer Optimization paradigm. Strict boundaries between isolated ISO/OSI layers are broken up, the total number of layers is reduced (network, control and application layer), functionality is aggregated through the Cross Layer approach and direct communication is enabled between network, control and application layer for End-to-End optimizations. Cross Layer Optimization is investigated in the research, but has not been widely introduced in productive networks.

Figure 1.1 illustrates two different views on Cross Layer Optimization enhancements for the ISO/OSI Reference Model. These two different architecture models have been summarized as part of the related work section presented under 2.2.7 of Chapter 2 and under 4.2 in Chapter 4.

The Dynamic Simplified ISO/OSI Model in the upper right corner of the figure depicts the reduction of layers from seven independent down into three layers. The central layer is the Mediation layer, which is in the focus of this thesis. This model also motivated by Foukalas et al. in [10] should point out the high interaction between the three remaining layers.

The other view on Cross Layer Optimization enhancements for the ISO/OSI Reference Model also motivated by Carneiro et al. in [11] and Kellerer et al. in [12] is depicted as External Cross Layer Optimization in the lower right part of the Figure. This figure illustrates the external Cross Layer control while keeping the layers unmodified.

Within fixed core networks, but especially within radio communication, in which the transport medium is shared among all communicating instances, the situation of assuring dedicated resources to critical services is getting more complex. As

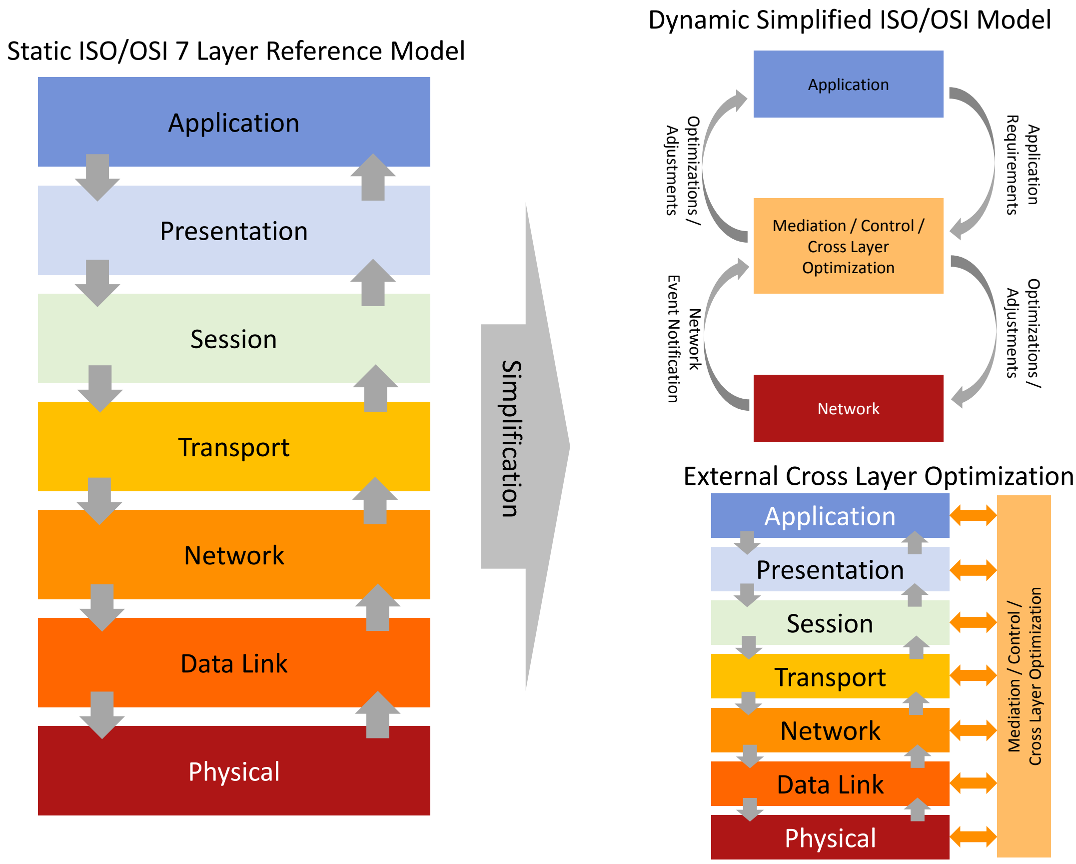

Figure 1.1: Cross Layer Enhancements for the ISO/OSI Reference Model

today's Internet relies on the best effort IP transport principle, the Fixed and Mobile Broadband Telecommunication Networks have new requirements on the transport network, which are not fulfilled yet. Especially the mobile access and core network is over-provisioned to ensure reliability, inflexible in regard to dynamic scalability and not capable of flexible provisioning of new network functions or services.

Virtualization concepts enter the telecommunication domain at this point in time and two new main trends on telco virtualization emerge. First, the paradigm of Software Defined Networking (SDN) [13] separates control and data plane through extracting routing logic out of data plane elements into centralized controllers. Second, the concept of Network Function Virtualization (NFV) [14] decouples software from dedicated hardware and thus enables the hardware-independent deployment of Virtual Network Functions on commodity server hardware.

Finally, the convergence of networks enables All-IP communication and the influence of virtualization evolves the telecommunication market from a product to a service based environment.

New challenges and opportunities arise, which are presented and discussed in the following sections.

1.2 Terms and Definitions

This section introduces the most relevant terms and definitions used within this thesis. Common terms defined and formulated in standardization organizations have been referenced and adopted in the wording of this thesis work.

The following list provides the reader with the required terminologies and definitions of key fundamental terms to understand this document:

Flexibility The ability of a system to adapt dynamically to external or internal influences.

Generic The term generic in the information technology domain refers to a generalized abstract model of one or more specific exemplars. Such a generic model consists of common methods and attributes, which are also applicable to the specific exemplar.

(ISO/OSI) Layer A set of specific features and functionalities, which are aggregated into specific groups and interconnected over well-defined interfaces. The ISO/OSI Reference Model consists of seven layers.

Cross Layer The scope of the term *Cross Layer* in this regard refers to two dimensions. The first dimension is vertical and includes the ISO/OSI layers. The second dimension is horizontal and includes the End-to-End (E2E) view of a service data flow starting at the User Equipment (UE), traversing the access, core and backbone networks and terminating at the service.

QoS The collective effect of service performance which determines the degree of satisfaction of a user of the service. The International Telecommunication Union ITU-T Recommendation E.800 [15] provides the basic definition of Quality-of-Service (QoS) as follows: *'Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service.'*

Next Generation Networks (NGN) An access network independent All-IP platform offering triple play services (voice, video/TV and Internet) and consisting of three layers: Application, Control and Network.

Mobile Broadband IP-based service for a mobile device enabled through telecommunication technologies. The evolution of Mobile Broadband network is characterized through increasing higher peak data rates, additional frequency bands, wider channel frequency bandwidth, reduced delay and improved QoS support. Next Generation Mobile Broadband networks are going beyond the standard of the fourth generation represented by Long-Term-Evolution (LTE), High Speed Downlink Packet Access (HSDPA)+ and 802.11ac.

Virtualization The two main aspects and trends emerge in the virtualization of telecommunication environments. One of them are SDN defined and specified by OpenNetworking Foundation (ONF) as 'Physical separation of the network control plane from the forwarding plane' in [13]. A second concept is NFV analyzed by ETSI Special Interest Group NFV, which addresses the decoupling of software from dedicated hardware. Modular Virtual Network Functions (VNF) are enabled to run on Common Of The Shelf (COTS) hardware [16].

A complete list of terms used in this thesis is provided in Annex A.

1.3 Problem Formulation and Statement

The performance of Fixed and Mobile networks is increasing continuously in nearly all parts of the world, but mainly in industrialized countries [1] as indicated in the previous section briefly. The overall radio access network density is growing; additional novel radio access network technologies like WiMAX, HSDPA and LTE are being deployed.

Fees for mobile data subscriptions (especially telephony and Internet flat rates) are becoming cheaper, due to the large number of (virtual) operators on the market. 120 of 515 active companies were offering mobile broadband services using another operator's network worldwide [17] in June 2011.

Today, the Internet is the largest globally recognized communication system, which has continuously evolved in dimensions of technology, available capacity, number of subscribers, total transported data [18, 1, 19], involved devices [20], etc. since its beginnings in the 1960's [21].

As the world moves towards a data-only All-IP network environment with WiMAX, LTE and its advanced version (LTE-A), it is crucial to ensure Quality-of-Service even during overload situations in the access and core network.

In addition, application driven control of the network is envisioned by network operators, service providers and as part of international research projects of the academia [22, 23, 24, 25].

In this approach, applications are enabled to signal dedicated resource demands into the network according to the service data flow. Instead of transporting all IP data packets with the same priority, this concept of application-aware networking enables a more efficient utilization of network resources and raises the subjective Quality of Experience for the customer.

According to the white paper of CISCO [1] (Feb 2013) the top 1 percent of mobile data subscribers are responsible for a disproportionate amount of mobile data traffic with 16-18 percent. Around 50 percent of the overall data transport is caused by the top 10 percent of mobile data subscribers.

New concepts for data rate performance improvements take carrier aggregation, multipath and dual or multi radio into account. Available radio resources are added, the data stream is divided among the heterogeneous connections and a larger total capacity is achieved.

Global mobile data traffic grew up to 70 percent in 2012 and mobile video will continue to dominate the traffic share with about 66 percent until 2017. Mobile network connection speed has more than doubled in 2012 and average speed will grow at a compound annual growth rate of 49 percent, and will exceed 3.9 Mbps in 2017. In 2012 a fourth-generation (4G) connection generated 19 times more traffic on average than a non-4G connection. Although 4G connections represent only 0.9 percent of mobile connections today, they already account for 14 percent of mobile data traffic. Global mobile data traffic will increase 13-fold between 2012 and 2017 according to the forecast of CISCO. By 2017 there will be 8.6 billion handheld or personal mobile-ready devices [1].

A dominant part of this growth is taking place in industrialized countries, whereas in less developed countries even no Internet access or only very low bandwidth is available. Limited resources need to be shared in a smart way to provide optimized resource usage and end user satisfaction. Mobile devices like smart phones, tablets or netbooks are evolving in terms of features and performance. The performance of these devices with regard to computation (multi-core), battery lifetime, storage and connectivity over multiple radio networks is increasing, too, while the prices are normalized due to the large number of competing manufactures in the market. The freedom of choice out of a multitude of almost equivalent devices forces the manufacturers to lower the prices in order to challenge the competitors, which in turn increases the overall mobile device penetration.

The complexity of the network and its management is becoming more complex with the convergence existing and the introduction of novel technologies in parallel to existing deployments.

The convergence of networks generalizes the purpose of individual network transport technologies for the usage of multiple IP services in parallel. Table 1.1 summarizes the main network technology domains and telecommunication services. Isolated silo solutions have been primarily constructed, in which exactly one technology has been used for only one specific service. Initially and traditionally a one-to-one mapping of technology and service could be found.

The situation changed over time and nowadays the convergence of networks opens up network technologies for different IP services. Circuit-Switched networks are continuously replaced by Paket-Switched networks due to the huge OPEX, CAPEX but limited capacities and spectrum efficiency in comparison to All-IP networks. Information (voice and other data) is transported in All-IP networks in the form of packets without taking individual application characteristics into consideration.

Different application requirements on the packet data transport within the network exist due to the heterogeneity of applications. Unfortunately those application requirements cannot be realized adequately yet, because of missing communication between the application and network layer.

In this time in which the Internet and telecommunication networks have entered critical infrastructures and systems, it is of high importance to guarantee service data rates, QoS and reliable data transport.

Technology	Telephony	Television	Radio	Data	Content Sharing
Satellite	New	Initial	New	New	New
Cable	New	Initial	New	New	New
Cellular	Initial	New	New	New	New
Fixed Line	Initial	New	New	New	New

Table 1.1: Taxonomy of Initial and New Technologies and Services Domains in Converged Networks

Signaling, voice, video, emergency service and Over-The-Top services are transported equally within an All-IP network. Overload situations and resource limitations cause packet loss, degraded subjective user experience or connectivity interruptions. Usually signaling and emergency real-time multimedia services require a higher level of QoS in contrast to non critical services (file downloading, cloud synchronization, etc.). Those services need to be identified, signaled between application layer and network layer and finally treated properly according to their individual requirements. These requirements are not reflected within the current telecommunication network architecture.

The presented network technologies (satellite, cable, cellular and fixed line) have been designed separately from each other and each has been dedicated to a specific service type. Services evolved independently on top of each network technology, which led to the problem of having similar services realized for different networks. Changes of existing services and the introduction of new services have become complex tasks.

At this point the convergence of networks aggregates and abstracts networks and therefore introduces a transparent layer between underlying network technology specific details and services above. The abstraction on the IP layer enables a converged All-IP network using a singular service realization for multiple network technologies at the same time.

Table 1.1 illustrates the convergence of network technologies and depicts the initial services supported through this technology as well as later added new services.

Services are no longer realized specifically for one network technology nor are networks purely designed service specific. Control and management take place in the network as well as in the application layer.

From an End-to-End perspective, current networks are divided into multiple parts each having dedicated functionalities. Today's telecommunication networks consists of the following conceptual parts: Access Network (AN)/ Radio Access Technology (RAT), Core Networks (CN), Services and Applications and Backbone (BB)/Backhaul (BH). The individual parts of a network are controlled and managed independently of each other.

The design of the Internet as an open communication system enables a rapid deployment (fast time-to-market) of new IP applications for a multi-million person audience in the domains of social networks, communication, entertainment, business sectors (health, travel, finance, education, cargo, etc.). 3rd-party Over-The-Top Application Programmable Interface (API) as well as telco open walled-garden opens up service environments in a simplified way for application development.

Statistics in early 2012 estimated an availability of around 450.000 mobile applications (apps) for Android. Google announced during the sixth annual I/O developer conference (2013) in San Francisco the activation of 900 million Android devices and a total amount of 48 billion downloaded and installed applications [26]. The market figures for the ITunes store of Apple are comparable in their size.

Basic telco services such as messaging, voice, presence, chat, etc. have been exposed, but improvements such as Cross Layer communication and optimization have been disclosed. Therefore most of the mobile apps are requiring a permanent Internet connection for synchronization, advertisement or interaction, which leads to higher resource utilization in the telco infrastructure.

The strong competition between Telecommunication Service Providers is tightening the revenue with continuously falling tariff models. Latest statistics of ITU 'Facts and Figures' [27] in 2013 indicate the number of subscriptions approaches global population in 2013. The mobile cellular penetration reaches 126% in Europe in comparison to 63% in Africa and 170% in Commonwealth of Independent States (CIS). These facts means that European TSPs have more difficulties in acquiring new customers, because of the already high subscriber penetration. Differentiation in terms of service spectrum and quality will become the key denominator to attract customers.

According to Deloitte 'MCNO Competition Strategy Analysis' [28] the number of Mobile Virtual Network Operators (MVNO) grows in 2013 up to 1207 worldwide and 723 MVNOs in Europe. The MVNOs operate on top of the physical network of a TSP, have no or limited own infrastructure elements and mainly have rented dedicated virtual resources from the TSP for operating their subscriber.

EU commissioner Neelie Kroes plans to remove roaming costs for TSPs until 2015, which reduces their revenue further.

As a result all TSPs and MVNOs will compete for the customer/subscriber - at least in Europe - which will reduce the subscription fees further.

As one of the key requirements for Future Networks flexible convergence and optimized End-to-End connectivity are expected even in changing environmental conditions flexible as it is stated in various position papers [29], white papers [30] and network operators announcements [30]. Figure 1.2 summarizes the relevant key features and requirements of the new network telco infrastructure as envisioned through the influences derived out of the above mentioned sources.

Traditional mobile broadband networks will not cope with these huge IP data traffic demands, since their intentional conception was not meant to serve huge amounts of data on the last mile over radio. New solutions need to be developed for solving the expected saturation of Fixed and Mobile access and core networks in order to avoid and solve Radio-Access-Network (RAN) congestions.

In order to address today's limitations and to develop solution concepts accordingly, basic principals and fundamental questions have to be answered. A set of

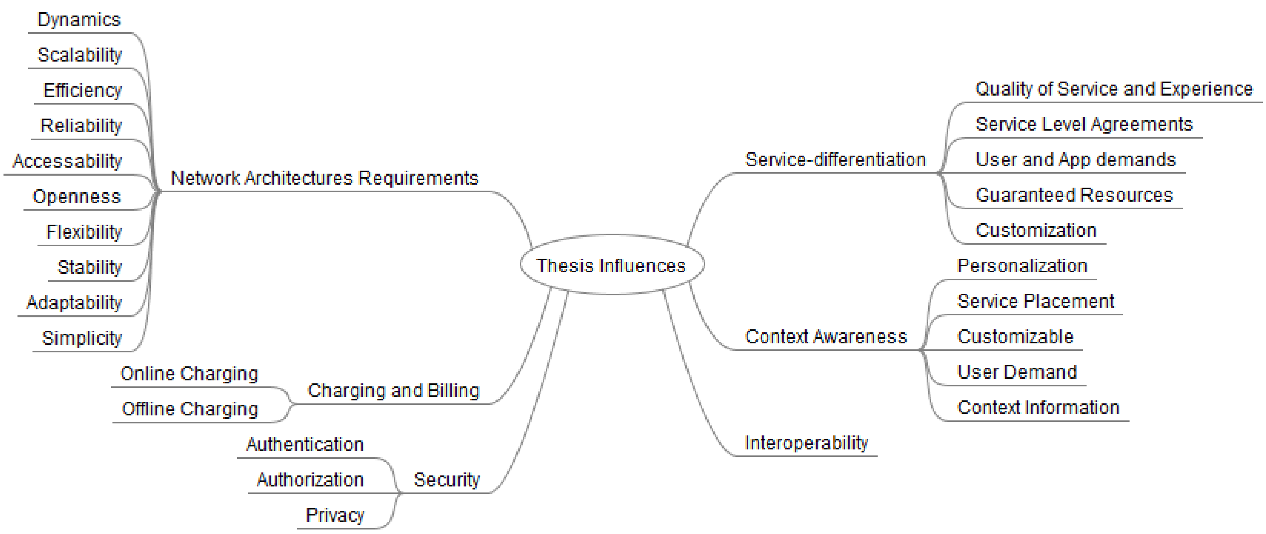

Figure 1.2: Thesis Influences

questions address the main challenges, opportunities, limitations, implications and expectations in regard of virtualization in telco networks. Other questions are targeting value added features and services (QoS on demand, network-aware services, dynamic service chaining) of software defined telco networks and will review their importance in future telecommunication networks. An evaluation of the dependency between complexity, scalability, reliability and flexibility for virtualization in telco networks has to be performed.

New questions arise while applying virtualization on telecommunication networks. New ideas, concepts, methods and strategies have to be investigated, in order to meet those new requirements.

Cross Layer service control mechanisms are candidate solutions for three main reasons:

1. Differentiate between service classes.

2. Optimize resource usage and network utilization.

3. Schedule the core network data transport more efficiently at the same time.

Quality-of-Service in today's network is solely network operator controlled through policy control elements.

Important aspects are missing in current QoS decision processes. The involvement of yet unused aspects like individual user demands, device and real-time network capabilities as well as the user context will optimize and improve the data transport significantly. The potential for new business models arises for network operators and service providers in this process. New concepts and network services are required to enable new Value Added Services (VAS), which are discussed in the following.

1.4 Research Hypothesis and Question

The previous section 1.3 on Problem Statement creates a broader picture for understanding challenges on today's and future networks. This section now formulates the main research question, which covers a subset of all aspects of the broader picture. Additionally, the research question is divided into sub-research questions, each of which specifies certain aspects in detail.

The research question has been derived out of the referenced documents cited in the section on problem statement.

The main research question addressed by this thesis is:

> ***'Is the Cross Layer Optimization paradigm applicable to Fixed and Mobile Broadband Telecommunication Networks and Beyond?'***

The secondary research questions derived as aspects of the main research question are:

1. What are the existing service control functions, protocols and solutions in mobile telecommunication networks?

2. What are the key design features for a Cross Layer Optimization conceptual model and its specification?

3. What are the benefits and limitations of applying the Cross Layer Optimization paradigm to mobile telecommunication networks?

1.5 Scope of the Thesis and Scientific Contribution

This section positions the thesis' scientific contributions and scope within the context of NGN and FI.

1. Classification and discussion of several service control mechanisms for IP based service delivery within Fixed and Mobile Next-Generation-Networks and beyond.

2. Analysis of existing service control mechanisms in terms of functionality.

3. Design and specification of basic core functionalities for controlling IP data traffic initiated in the service domain, going through the core- and access network towards the device.

4. Providing a prototypical reference implementation of the core functionalities and disseminating results through publications, contributions to technical specifications and related standardization bodies.

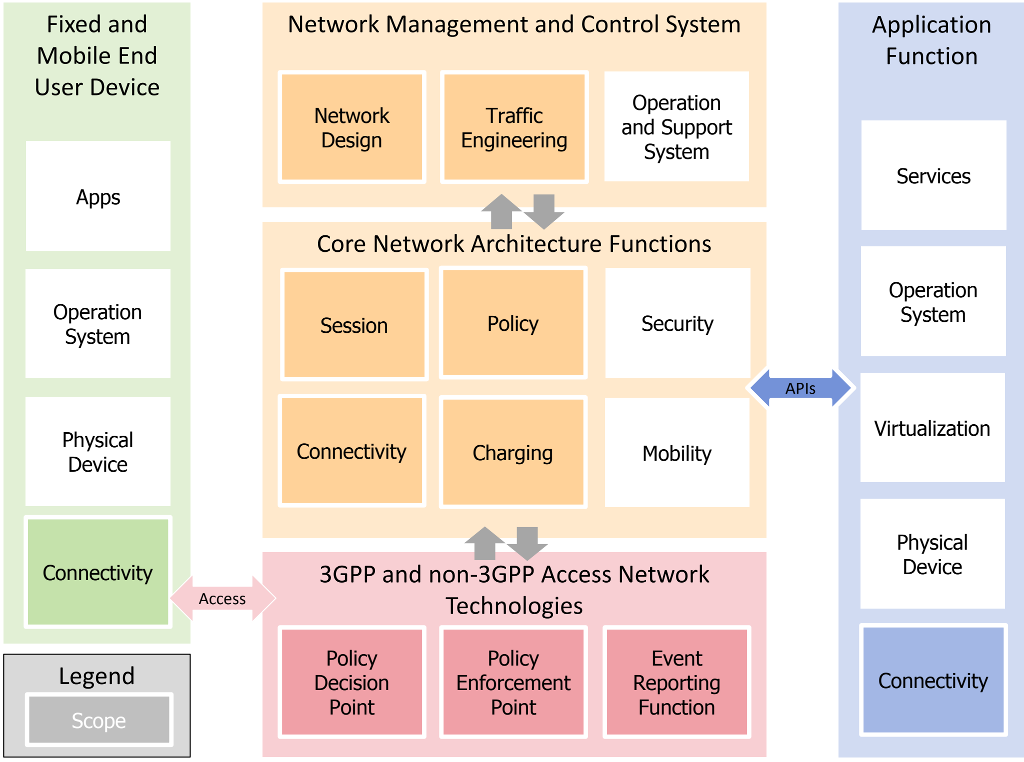

Figure 1.3: Thesis Scope - Outlined Functional Elements and Reference Points

Figure 1.3 positions the thesis' scope within a Fixed and Mobile Broadband Telecommunication Network architecture. Three domains - each depicting several functional blocks - have been identified, in which the scope is highlighted.

The main goals of this research work and contributions are listed as action points:

- Service control mechanism analysis in Fixed and Mobile broadband networks and the Future Internet: Identification, classification and discussion.
- Identification of high level, functional and non-functional requirements derived from different stakeholder and use-case scenarios.
- Gap analysis between related work and requirements.
- Definition of key design principles and specification of a conceptual model for Generic-Adaptive-Resource-Control (GARC).
- Implementation of core functionalities of GARC and providing a reference implementation as prototype.
- Integration of theoretical concepts and practical implementations into the NGN2FI playground [31] as well as into Fraunhofer FOKUS software toolkits as scoping exercise.

- Prototype validation through selected use-cases and critical reflection of the prototype against requirements.
- Conclusion of the work, outline of future work and further study.
- Documentation of research and findings in the scope of this thesis and beyond.

1.6 Methodology of this Thesis

This section outlines and motivates the methodology used for achieving the objectives of this thesis. The main objective of this thesis is the design, implementation and evaluation of a Cross Layer Optimization concept on telecommunication networks.

A major emphasis is given to the definition of a theoretical model and its practical realization through the implementation of a Cross Layer network resource optimization system for telecommunication systems.

Figure 1.4 illustrates the trends and influences on the thesis, which are basically the telecommunication ecosystem and new requirements, virtualization concepts represented through SDN, NFV and Cloud as well as Next Generation Network technologies. This thesis is positioned at the thematic overlap of the presented main streams and analyzes the influence and impact of Cross Layer Optimization on this novel telecommunication environment.

Different project management forms were analyzed at the beginning of this thesis. Given the structure of work, a linear waterfall model seemed most applicable in comparison to agile or extreme approaches. Finally it is expected to have the individual phases concluded sequentially, without facing radical changes at a later point in time.

Figure 1.5 of this thesis work flow is aligned to the enhanced waterfall model that describes a sequential software development process that passes through several phases and is the life cycle of the dissertation.

The phases of the thesis are structured as follows. The outcome of each phase contributes to the above mentioned chapters.

1. Study of Fixed and Mobile NGN in their evolution towards FI.
2. Identification of technology specific service control mechanisms on several logical layers in NGN and FI.
3. Taxonomy creation of service control mechanisms.
4. Specification of a generic Cross Layer Service Control optimization functionality.
5. Implementation of a generic Cross Layer Service Control optimization functionality.
6. Integration into the NGN2FI.org playground.

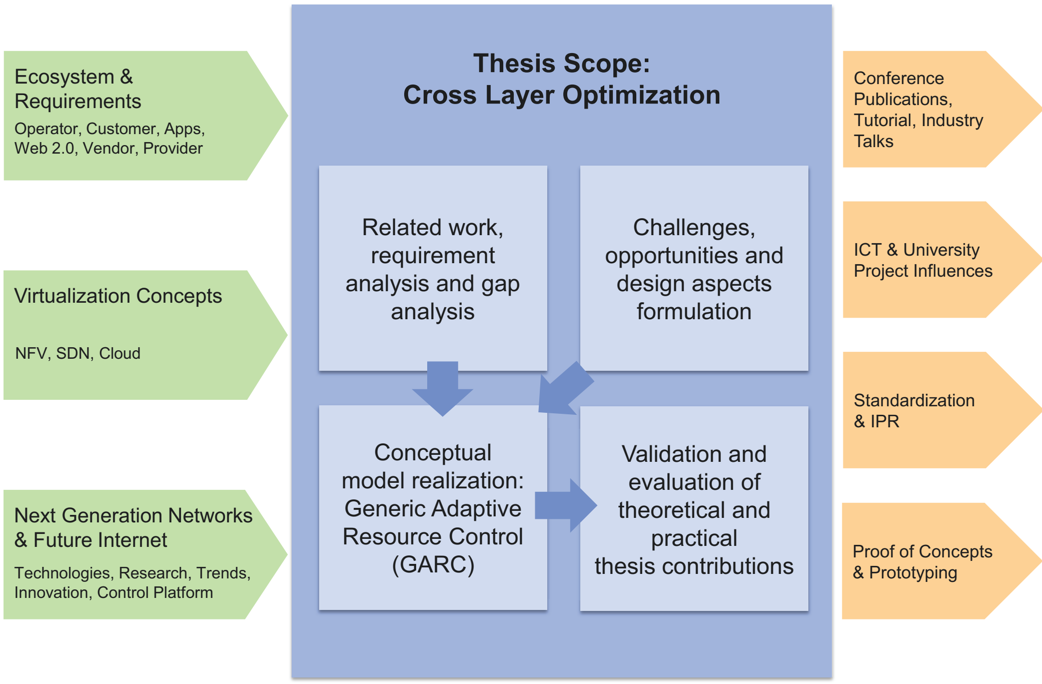

Figure 1.4: Trends, Influences and Technology Evolution

7. Test and evaluation of the implementation.

8. Documentation of research and findings.

1.7 Outline and Document Structure

After the first chapter, six other chapters have been formulated as follows.

Chapter 2 on Related Work introduces important concepts in the scope of the thesis as technical foundations. These concepts cover technical standards, technologies, publications, initiatives and standardization bodies as well as international Information and Communication Technology (ICT) research projects, QoS control and optimization. All above mentioned domains are analyzed and the most important facts and aspects are summarized in this section. Finally, a taxonomy positions the related work and a comparison summarizes the evaluation of them.

Chapter 3 on Requirements Analysis aggregates different sources of requirements and summarizes the most relevant high level, technical and non-technical requirements. A discussion and gap analysis compares State of the Art from Chapter 2 with requirements analyzed within this section. A summary highlights the major findings and concludes this section.

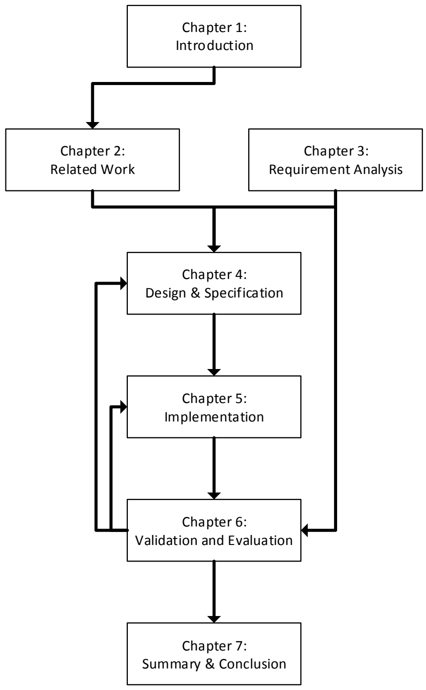

Figure 1.5: Dissertation Methodology

Chapter 4 on Cross Layer Optimization Concept and Specification first presents a *Research Discourse* on the *Design Aspects* in Subsection 4.2. The Research Discourse points out key Design Aspects and life cycle phases for Cross Layer optimization functions. The structure of Chapter 4 is aligned with 3GPP starting with a functional architecture model followed by an element and reference point specification. Cross Layer interaction models and use case scenario definitions illustrate message flows and sequence diagrams for Cross Layer service optimizations.

Chapter 5 on Cross Layer System Architecture Model Implementation summarizes the software technical aspects of the Cross Layer optimization system implementation. Relevant Open Source software tools are listed in the beginning of this chapter. The main part of this chapter is again structured and aligned to the 3GPP technical specifications beginning with Architecture Model and High Level Function, Reference Points and Information Flows and Major Reference Points implementation. A summary concludes this chapter with key findings while implementing the Cross Layer Optimization function.

Chapter 6 on Validation and Evaluation compares the requirements identified in Section 3 with the implementation presented in Section 5. After the presentation of the concept and its implementation, this section validates the previous sections through extensive test scenarios and discusses the results.

Chapter 7 as a Summary recapitulates the major findings of all previous sections and affirms the initial research questions out of Section 1.

Chapter 2

Related Work and State of the Art

This chapter highlights related work, which influences Cross Layer Optimization, Service Control Mechanisms (SCM) and Quality of Service (QoS) control in fixed and mobile Next Generation Broadband Networks and the Future Internet.

A lot of research and development has been done in the scope of this chapter. Therefore a pre-selection of network technologies and protocols was done, in order to limit the scope of this chapter. A particular focus was placed on 3GPP standards of IP Multimedia Subsystem and Evolved Packet Core as well as related IETF protocols. Network virtualization as one aspect of the future Internet has been investigated in addition in the form of software defined networks and network function virtualization. Several approaches have been identified, summarized and grouped into four main subsections. First, key standardization activities for fixed and mobile network control of PacketCable, DSL Forum, ETSI, ITU-T, 3GPP and IETF are presented in form of QoS architecture models and QoS control protocols. The second subsection discusses several academic works, which is followed by a third subsection presenting International research projects that cover QoS control. In subsection four, commercial products for (Cross Layer) QoS control are presented and discussed. Furthermore, an extensive evaluation compares the presented related work within a taxonomy and a summary concludes the chapter. [1]

QoS involves all main parts of the horizontal dimension data transport chain starting from the user equipment, over access-, core- and backbone-network towards the service. All these components can be split again on the vertical dimension into network-, control- and service-layer on which QoS control is applied or enforced. A vertical dimension includes the per definition independent classic ISO/OSI layer reference model, which effects the Cross Layer QoS control on different layer as well.

Traditional Quality-of-Service approaches for IP networks consist of resource reservation (IntServ) or service class packet-labeling (DiffServ) mechanisms next to the best-effort packet-transport paradigm. The concept of Next-Generation-Networks (NGN), which separates data- and control-plane concept wisely, decouples data traffic from outbound signaling transport wise. A policy controller in NGN combines signaling and data transport logically and performs charging, QoS as well as Authentication, Authorization and Accounting (AAA) and is designed to support roaming cases over heterogeneous network types.

Three strategies for facing the lack of bandwidth in overload situations exist in today's telecommunication networks and are discussed among network operators at conferences [43, 2, 3, 44], white paper [45] and in interviews:

- Over-provisioning of the access and core network or data center. Geographical redundancy is one of the common techniques to improve system performance and reliability, by increasing costs at the same time. Resource elasticity is a common approach in cloud environments, in which resources are 'hot' migrated.

- Traffic engineering paired with smart data traffic control and management

[1] Results of this chapter have been published in book chapters [32, 33, 34], journal papers [35, 36] and conference papers [37, 38, 39, 40, 41, 42]

optimizes fixed resources in an optimal way.

- Hybrid approach: a combination of the over-provisioning and traffic engineering strategy.

Over-provisioning in this context means usage of additional radio antennas, frequency spectrum, 3GPP Diameter Routing Agent (DRA) or GSMA Diameter Edge Agent (DEA), WiFi-offload, femto-cell-deployment, etc, which in turn all leads directly to an increase of CAPEX and OPEX on the network operator side. Over-provisioning of all kinds of data transport involved components is beyond the scope of this work and is not addressed.

2.1 Key Standardization Activities

This section discusses key standardization activities on QoS control architectures of CableLab, DSL Forum, MultiService Forum (MSF), ETSI, ITU-T and 3GPP. The here named organizations focus on different standardization aspects of QoS, which are explained in detail in the following. In general, ETSI and ITU-T propose a similar but not equal QoS core architecture technology solving specific challenges on layer 2 and layer 3, while CableLabs and DSL Forum focus on challenges on specific transport network technologies. ETSI defines the Resource Admission Control System (RACS) [46] and ITU-T defines Resource-Admission-Control-Function (RACF) [47] both present generalized approaches applicable to heterogeneous network types. The scope of RACS covers the access and edge network whereas RACF covers the access- and the core network. Therefore RACS can be seen as subset of RACF.

2.1.1 CableLabs

CableLab defines in PKT-SP-QOS-I02-080425 [48] a dynamic QoS (DQoS) control PacketCable 2.0 Architecture for hybrid fiber and coaxial (HFC) networks. The architecture defined by PacketCable 2.0 takes advantage of 3GPP IMS features and capabilities while making use of the rich set of QoS capabilities provided by PacketCable Multimedia. PacketCable Multimedia defines an IP-based platform for delivering QoS-enhanced multimedia services over DOCSIS 1.1.

The PacketCable Application Manager (PAM) determines QoS resources needed for the active session, based on the received session descriptors from P-CSCF and managing the QoS resources allocated for a session. PAM in conjunction with the Policy Server (PS) fulfills the role of the Policy and Charging Rules Function (PCRF) in the 3GPP IMS PCC architecture. Cable Modem Termination System (CMTS) implements the role of Policy and Charging Enforcement Function (PCEF) in the 3GPP PCC architecture.

PacketCable 2.0 supports AF interaction, making use of the 3GPP Rx reference point. In addition, 3GPP Gx is supported between the PS and CMTS. No reference point similar to 3GPP Gxx is specified.

Upstream bandwidth sharing between multiple cable modems (CM) and the Cable-Modem-Termination-System (CMTS) is controlled by layer 2 MAC protocol called Data-Over-System-Interface-Specification (DOCSIS).

A mapping of AA-Requests to Gate-Set functionalities makes use of FlowSpec Traffic Profiles. These profiles are realized through an Integrated Services (IntServ) architecture. FlowSpec is defined as combination of the traffic description known as a TSpec and the resource requirements are contained in an RSpec.

TSpec consists in detail of Bucket depth (b) measured in bytes, Bucket rate (r) in bytes/second, Peak rate (p) in bytes/second, Min policed unit (m) in bytes and Maximum datagram size (M) in bytes. RSpec consists in detail of Reserved rate (R) measured in bytes/second and Slack term (S) in microseconds.

2.1.2 DSL Forum

The DSL Forum defines a layer 2 dynamic QoS resource control for Digital-Subscriber-Line (DSL) in the home network. Connectivity in a DSL network involves four important network elements. One or multiple User Equipments (UE) are connected over Ethernet or WLAN to the Customer Premises Equipment (CPE) (residential gateway). The CPE is connected over ATM to the Digital Subscriber Line Access Multiplexer (DSLAM). The DSLAM is further connected over ATM to the Broadband Remote Access Server (BRAS). PPP over Ethernet (PPPoE) sessions are established E2E finally over all four network elements. The DSL modem (CPE) and the DSLAM are then connected over an exclusive line and therefore do not need QoS control on this connection. The data transport over ATM requires the Layer Two Tunneling Protocol (L2TP) [49] implemented in a L2TP Access Concentrator (LAC) and L2TP Network Server (LNS) functionalities for efficient data transport.

2.1.3 European Telecommunication Standardization Institute

The European Telecommunication Standardization Institute (ETSI) specified a NGN QoS control architecture aligned on the work done by ITU-T in parallel. The ETSI QoS NGN reference model consists of Network Attachment Subsystem (NASS) and Resource Admission Control System (RACS) [46].

NASS provisions IP addresses dynamically, authorizes the User Equipment (UE) at the IP level, authenticates network access based on user profiles and adapts the network configuration based on user profile and location.

RACS implements admission control to the access and aggregation segment of the network [46]. Furthermore RACS provides policy-based transport control services to applications. This in turn enables the request and reservation of transport resources from access and core transport networks within its coverage, which also include points of interconnection between them in order to support E2E QoS. RACS is the NGN Subsystem responsible for elements of policy control, resource reservation and admission control.

These are in detail:

- Admission Control: RACS implements Admission Control to the access and aggregation segment of the network.
- Resource reservation: RACS implements a resource reservation mechanism that permits applications to request bearer resources in the access, aggregation, and core networks.
- Policy Control: RACS uses service-based local policies to determine how to support requests from applications for transport resources.
- NAT traversal and NAT/Gate control functionality.

The Service Policy Decision Function (SPDF) is a Functional Entity that acts as a final Policy Decision Point for Service-Based Policy control (SBP) for each administrative domain it resides in. The Gq' enables the NGN Sub-Systems to interact with the RACS for authorization, resource reservation and Border Gateway Services (BGS). The generic Resource Admission and Control Function (x-RACF) is a Functional Entity that acts as a Policy Decision Point (PDP) in terms of subscriber access admission control, as well as in terms of resource handling control. The generic Resource Admission Control Function receives requests for QoS resources from the SPDF via the Rq reference point, or from the RCEF via the Re reference point, indicating the desired QoS characteristics (e.g. bandwidth). The Border-Gateway-Function (BGF) is a packet-to-packet gateway for user plane media traffic, which performs both policy enforcement functions and NAT functions under the control of the SPDF in each of the network segments: access, aggregation and core. The Resource Control Enforcement Function (RCEF) performs policy enforcement functions in push mode under the control of the x-RACF or in pull mode after receiving a request from the Basic Transport Function (BTF) [46].

The Application Functions (AFs) or an interconnected SPDF are enabled to demand QoS from the network using policy request towards a SPDF.

2.1.4 International Telecommunication Union

The International Telecommunication Union (ITU-T) presents in X.641 a recommendation as a common basis for the coordinated development and enhancement of the wide range of standards specifying or referencing Quality of Service (QoS requirements or mechanisms in an Information Technology (IT) environment. In particular ITU-T recommends a QoS framework in X.641, which consists of QoS management functions (QMF), QoS monitoring and QoS validation functions. A QoS requirement parameter semantic is presented, which describes a parameter with its upper or lower limit; an upper or lower threshold; and an operating target [50, p.23].

The ITU-T specified NGN reference architecture of Y.2012 [51] in 2007 is summarized in the following.

According to ITU-T.E.800, 'It is up to the Service Provider to combine different network performance parameters in such a way that the economic requirements of the Service Provider as well as the satisfaction of the User are both fulfilled.' [15]

NGN Reference Architecture The NGN reference architecture defined by ITU-T consists of a service stratum, an underlying network transport stratum and reference points.

The four main reference points specified by ITU-T and connected with the NGN reference architecture are 1) User-to-Network-Interface (UNI), 2) Network-to-Network-Interface (NNI) and 3) Application-to-Network-Interface (ANI) and 4) Service-to-Network-Interface (SNI).

The four reference points of the ITU-T NGN reference architecture and its functionalities are:

- UNI signaling system specified in Q.3402 provides control and data plane connectivity between the terminal and the network.
- NNI signaling system specified in Q.3401 provides pure connectivity over NGNs at the service or transport stratum.
- ANI signaling system specified in Y.2012 offers capabilities and resources needed for realization of applications without involving media plane transport. Two of three main characteristics are important for this work and are a) agnosticism and b) accessibility as outlined in the following. Application support and service support functions areas consist of functions that are agnostic with respect to their underlying NGN infrastructure. Support for open network-agnostic service interface provides an abstraction of the underlying network capabilities.
- SNI signaling system specified in Y.2012 is the realization of the service or content provider access interface (SPAI) specified in ITU-T Y.140 and provides a control and data plane interface for exchanging information between NGN and Service Providers.

Signaling between elements of the NGN reference architecture is defined in [52]. Session Initiation Protocol (SIP) is recommended for multimedia control, session setup and termination, QoS negotiation and SDP transport. The Real-time Transport Protocol (RTP) is defined in Q.3401 and Q.3402 and is recommended for data transport over RTP between communicating end points.

Service Stratum Functions Service control functions (SCF) defined as Service control and content delivery functions (SCF and CDF). SCF include Functional Entities (FE) for media resource control, authentication and authorization, user profile, Access Gateway control and User signaling interworking. Application support functions and service support functions (ASF and SSF) enrich the service control spectrum further on through own AAA.

Transport Stratum Functions Transport Control Functions on top of Transport Functions build the Transport Stratum defined by ITU-T in Y.2012 [51].

The transport stratum of NGN defined by ITU-T provides the IP connectivity services to the NGN users under the control of transport control functions, including the Network Attachment Control Functions (NACF), the resource and admission control functions (RACF) and mobility management and control functions (MMCF).

ITU-T specified with Transport Control Functions three main functional elements within the NGN architecture [53, 54] controlling the transport plane namely Access Transport. These functional elements are:

- Network-Attachment-and-Control-Function (NACF) allocates and provisions IP addresses user profile based authorization and access network configuration [55].
- Resource-Admission-Control-Function (RACF) acts as the arbitrator between service control functions (SCF) and transport functions for QoS [56, 47, 57] related transport resource control within access and core networks.
- Mobility-Management-and-Control-Function provides IP based mobility on the transport stratum [51].

The Resource and Admission Control Functions (RACF) abstracts from transport network infrastructure to service control functions (SCF) and makes service stratum functions agnostic to the details of transport facilities, such as network topology, connectivity, resource utilization and QoS mechanisms and technology, etc. RACF arbitrates between service control functions and transport functions for QoS. In addition RACF performs policy-based transport resource control signaled by the Service control functions (SCF). RACF determines the transport resource availability and admission, and applies controls to the transport functions to enforce the policy decision, including resource reservation, admission control and gate control, NAPT and firewall control according to ITU-T.Y.2012 [51].

Access network transport functions forward user plane data and provide mobility, and apply QoS control mechanisms dealing directly with user traffic, including buffer management, queuing and scheduling, packet filtering, traffic classification, marking, policing, and shaping.

2.1.5 3rd Generation Partnership Project

In particular 3rd Generation Partnership Project (3GPP) and ETSI TISPAN defined the Next-Generation-Network (NGN) with the functional separation of network, control and data plane as well as differentiation between data and signaling. The IP Multimedia Subsystem (IMS) is presented as a session control architecture on top of a heterogeneous fixed and mobile telecommunication networks. Following the evolution of the standard from release 8 to release 12 the Evolved-Packet-Core (EPC) is introduced as All-IP network technology. A special emphasis lies on the

Policy-and-Charging-Architecture (PCC), which is applicable for both technologies IMS and EPC.

2.1.5.1 Evolved-Packet-System (EPS)

3GPP standardizes with the All-IP Evolved Packet Core (EPC) [34] in Rel. 12 a counterpart to the radio access network technology Long Term Evolution (LTE) and its evolution LTE-Advanced (LTE-A). EPC and LTE form together the Evolved-Packet-System (EPS) or Service-Architecture-Evolution (SAE). Figure 2.1 illustrates the main functional elements and reference points for the EPS. EPC provides network mobility between heterogeneous 3GPP [58] and non-3GPP [59] access network technologies, QoS through Policy and Charging Control (PCC), pure IP connectivity and security.

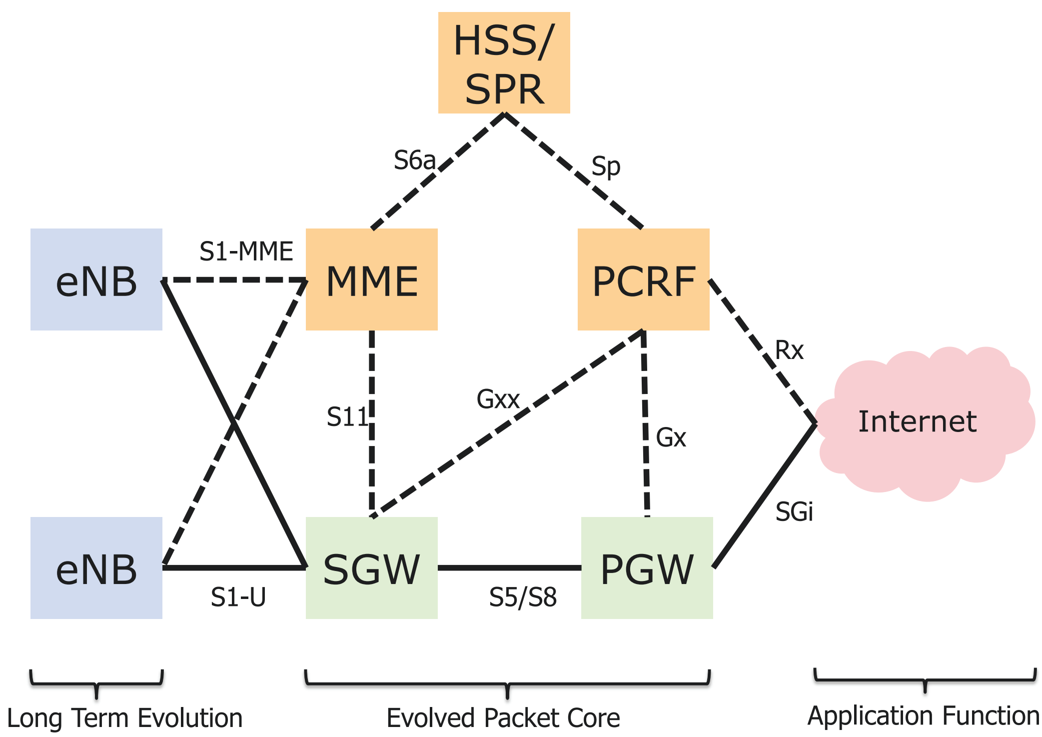

Figure 2.1: 3GPP Evolved Packet System Architecture

The network architecture of the Evolved-Packet-System (EPS) is flat in comparison to other mobile network technologies such as GPRS, UMTS, HSPA(+),WiMAX, LTE and LTE-Advanced. The flat architecture requires less components for providing end-to-end connectivity, which in turn, results in enhanced efficiency with smaller end-to-end delays. The Evolved-Packet-System in its minimal setup consists of only three key components, which are the Packet Data Network Gateway

(PGW), Serving Gateway (SGW) and Mobility Management Entity (MME). Other components are optional and futher enhance the functionality of the EPS. The most relevant functional elements are outlined in the following together with main reference points.

Key EPC Components and Protocols The key control node for LTE access is the MME, which is responsible for user tracking, SGW selection, Idle State control, and Bearer Control, which enforces user roaming restrictions. Two gateways are specified in EPS. The SGW acts as a mobility anchor for the user while it accesses the network through LTE or other 3GPP technologies (intra 3GPP handover), manages UE contexts, and controls the UE data path by terminating or re-establishing through paging requests depending on the current usage. The PDN Gateway provides connectivity from the UE to one or multiple external PDNs simultaneously. The PGW acts as a mobility anchor between 3GPP and non-3GPP technologies and performs packet filtering and charging.

Several protocols are used in the EPS within the different interfaces and on different layers for different purposes. The Internet Protocol (IP), Mobile IP (MIP) and variations, Proxy Mobile IP over IPv6 (PMIPv6), and GTP are used in the Network Layer for bearer control. The Transport Layer uses Stream Control Transport Protocol (SCTP) and TCP/UDP within the default or dedicated bearer. The Application Layer supports OMA Device Management (DM) currently only on S14 between UE and ANDSF, Diameter, and S1-AP. The two main protocols used in EPC are Diameter for security related functionalities and the GPRS-Tunneling-Protocol (GTP) in version 2 for mobility. Proxy-Mobile-IP (PMIP) single or dual stack for IPv4 or IPv6 are optional for client based mobility in EPC.

Additional and Optional EPC Components The Home-Location-Register (HLR) and Home-Subscriber-Server (HSS) are the main database of EPC subscriber information. Static user profiles as well as dynamic information like session contexts and locations are stored in the HRL/HSS. A Serving GPRS Support Node (SGSN) enables the delivery of data packets from and to mobile stations within its geographical service area. The SGSN supports mobility management, authentication, and charging in addition to packet routing and forwarding. The Access Network Discovery and Selection Function (ANDSF) was introduced as a new EPC element in Release 8. The ANDSF performs data management and controls functionality to assist the UE in the selection of the optimal access network in a heterogeneous scenario via the S14 interface. The EPC enriches its functionalities through the ANDSF, which aids in the access network (AN) selection process in the case of a handover. The handover process is supported by the ANDSF, which provides knowledge about adjacent ANs relative to the UE. AAA in the EPC are performed by the HSS, MME, and 3GPP AAA Server. AAA secures the user subscription, session key management, and security tunnel control.

The Evolved Packet Data Gateway (ePDG) attaches untrusted non-3GPP access networks like WLANs to the EPC. The ePDG performs important security functions, tunnel authentication and authorization, and IPSec encapsulation/de-capsulation of packets. Alternatively, trusted WLANs can bypass the ePDG and connect directly to the PDN gateway. These two alternatives are for trusted and un-trusted non-3GPP access networks connecting to the EPC. The Application Function (AF) is an abstraction of the service provider, which communicates with the PCRF to enable AAA at the application layer.

QoS Control within EPS The Policy Control and Flow Based Charging (PCC) architecture encompasses most of the QoS control mechanisms in 3GPP EPS. Additional QoS features not handled by PCC include Explicit-Congestion-Notification (ECN). In ECN IP packets are marked in the ECN-CE (Congestion Experienced) field through the evolved NodeB (eNB) for down link. The terminal adapts the rate in the following upon receiving such an explicit notification. The rate adaptation procedures defined in Rel-9 of in [4, 60, 61] are based on using ECN indications from the eNB to the UEs in the E-UTRAN. A study of use cases and requirements for enhanced voice codecs for the Evolved Packet System (EPS) including (AMR and AMR-WB) and the upcoming EVS codec has been done in [62]. The detailed adaptation algorithms and configuration parameters needed for ECN-triggered video rate adaptation should be studied and specified further in SA WG4.

2.1.5.2 Policy-Control-and-Flow-Based-Charging (PCC)

3GPP specifies with Policy-Control-and-Flow-Based-Charging (PCC) a flexible data plane control and charging architecture for IMS and Evolved-Packet-Core (EPC). The EPC enhances application layer functionality by introducing the Diameter [63] Rx interface [64] for demanding QoS explicitly for a specific connection. In particular 3GPP specified the Policy-Control-and-Flow-Based-Charging (PCC) architecture [65, 4] for 3GPP and non-3GPP networks. The PCC architecture consists mainly of Policy Decision Function (PDF), Policy Enforcement Function (PEF) [64] and Bearer Binding and Event Reporting Function (BBERF) [66]. The PDF determines policies within the Policy-Charging-and-Rules-Function (PCRF) which are enforced on the centralized PGW in EPC and validated on access network specific gateways providing SGW/AnGW/ePDG enabling BBERF functionality. The PCRF supports roaming over the S9 reference point between the PCRF in the home PLMN (also known as H-PCRF) and the PCRF in the visited PLMN (also known as V-PCRF)[67].

The PCRF encompasses two main functions control and charging:

Control within PCC The policy control encompasses control, QoS control, gating, QoS signaling, etc [68, 69]. Policy decisions are made in a PCC architecture based on user profile information mapped against static or dynamic network operator policies taking the context, access network and date into account. Nine Quality-of-Service-Class-Identifiers (QCI) characterize the spectrum of IP data traffic [70].

These are grouped into four real-time and five non-real-time groups each with individual delay and packet-loss thresholds.

Charging within PCC Flow Based Charging includes charging control and online credit control. Charging rules contain service data flow information and charging parameter. Classic charging models are volume based charging, time based charging, volume and time based charging, event based charging or no charging at all. Online (OCS) over Gy and Offline (OFCS) over Gz Diameter interfaces exists in the 3GPP standard. Online charging is characterized by user thresholds, which trigger a re-authentication request (RAR) on exceeding. The PCRF signals threshold values towards the PCEF, which in turn notifies the PCRF when reaching or passing such thresholds [71].

2.1.5.3 IP-Multimedia-Subsystem (IMS)

The IP-Multimedia-Subsystem (IMS) is an architectural framework for delivering SIP services to various fixed (cable, DSL), mobile (2G,3G) and wireless access (WiFi 802.11) networks. Its architecture was specified by 3GPP and uses SIP and Diameter protocols specified by IETF.

The IMS specification began in 3GPP release 5 as part of the core network evolution from circuit-switching to packet-switching and was refined by subsequent releases 6 and 7. 3GPP release 6 added inter working with WLAN to the IMS and enables Push to Talk over Cellular (PoC). Release 7 focuses on decreasing latency, improvements to QoS and real-time applications such as VoIP. Release 8 was frozen in December 2008 and covers LTE and All-IP Networks (SAE). Release 9 covers Wimax and LTE/UMTS interoperability. Release 10 contains LTE-Advanced as a major enhancement of 3GPP Long Term Evolution, which is discussed in the following sub-section on Evolved-Packet-System (EPS).

The IMS follows a three-tired architecture and consists of several components in which the three different CSCFs and the HSS represent the required core components of an IMS. All other components are used to enable optional service specific tasks to enhance the overall service spectrum. These components are grouped into the Service-, IMS- and Network layers, which are now presented in detail together with their individual key functionalities.

Core Elements of IMS The Call-Session-Control-Function (CSCF) is the name of a group of SIP servers or proxies which are used collectively to process SIP signaling packets in the IMS facing activities like call setup and termination, state and event management and address analysis, translation, modification if required and mapping of alias addresses.

The Proxy-CSCF (P-CSCF) is the first point of contact (outbound proxy) for the IMS UE and provides topology hiding. All SIP signaling messages from or to the UE are routed via the P-CSCF of the local (home or remote) domain. The P-CSCF is responsible for the security in the IMS and processes, validates and forwards requests to the desired destination. Registrations are forwarded further on to the home I-CSCF as well as requests which are also routed to the S-CSCF. Replies and incoming requests of other instances are forwarded to User Equipments on the downlink.

The Interrogating-CSCF (I-CSCF) assigns a S-CSCF to User Equipments by querying the HSS for the user profile. Thereby it queries the HSS using Diameter to retrieve the user location and to route SIP requests to its assigned S-SCSF. Up to release 6 of the IMS specification it was also used to hide the internal network topology (Topology Hiding Inter-network Gateway called THIG).

The Serving-CSCF (S-CSCF) acts as a SIP proxy, inspecting all messages to maintain a session state and to decide to which application server the SIP message will be routed. It interacts with the HSS through the Diameter interfaces Cx and Dx and the application service platform. Session information is collected by this IMS instance for charging.

The Home-Subscriber-Server (HSS) is the master database for controlling and managing static (IMSI, password, roaming policies, etc.) and dynamic (location, IP address, subscriptions, etc.) user profile information. It is connected to the application servers and through the Diameter Cx interface to the S-CSCF and the I-CSCF. The major tasks of the HSS are maintaining subscription-related information (subscription profiles), performing authentication and authorization of the user, providing user related information like location or network information, assisting I-CSCF in choosing the appropriate S-CSCF and enforcing provider policies (like De-registering users with invalid subscriptions).

2.1.6 Internet Engineering Task Force (IETF)

Internet Engineering Task Force (IETF) specified Integrated Services in the Internet Architecture and provides an overview in [72]. Today's networks carry out different types of services on the network such as network management, resource control and routing as well as on the application layer such as voice, video, ftp and email.

2.1.6.1 Resource-Reservation-Protocol (RSVP)

Resource-Reservation-Protocol (RSVP) [73] tracks a message between source and destination for traversing the network by listing all traversed router in a per-hop list. RSVP reservation message traversing the determined path in the exact opposite direction and reserving the resources finally. Possible QoS levels are rate-sensitive for a given data rate, delay-sensitive with a minimal delay or best-effort. RSVP requires support on every router in the network. Non-RSVP capable routers may violate the QoS reservation on the end-to-end data path over several autonomous networks.

2.1.6.2 Stream-Control-Transmission-Protocol (SCTP)

Stream Control Transmission Protocol (SCTP) is a transport layer protocol, which adopts parts of Transmission-Control-Protocol (TCP) and User-Datagram-Protocol (UDP). The SCT-Protocol is message oriented such as UDP and supports reliable transport with congestion control such as TCP as well [74].

2.1.6.3 Integrated Services (IntServ)

The IETF defined in [72] is an Internet service model that includes best-effort services, real-time services, and controlled link sharing. An application to network interface enables QoS requests. A service model is embedded within the network service interface invoked by applications to define the set of services they can request. Real-time QoS for a flow must invoke a local reservation setup agent. Resources (e.g., bandwidth) of individual connections must be explicitly managed in order to meet application requirements. Applications request requirements are signaled using the following Flow Specifications (Flow Specs): TSPEC (Traffic Descriptor) combined with the Token-Bucket-algorithm and RSPEC (Reservation Characteristics) within the TOS-Feld (Type of Service) of IPv4. Resource Reservation Protocol (RSVP) [75] is used for setting up an IntServ connection between two hosts.

The Integrated Service reference implementation framework includes four components: the packet scheduler, the admission control routine, the classifier, and the reservation setup protocol.

- Packet scheduler queues and manages the forwarding of different packet streams.

- Admission control implements a decision algorithm that a network element (router or host) uses to determine whether a new flow can be granted for the requested QoS without impacting earlier guarantees.

- Classifier maps incoming packets into types of classes, which may be performed based upon the contents of the existing packet header(s) and/or some additional classification number added to each packet.

- Reservation setup protocol, which creates and maintains flow-specific states in endpoint hosts and routers along the path of an individual flow.

A router monitor manages individual resources for a network element and decides individually to grant or revoke fixed value resource reservation for the complete duration of the session. Two traffic classes 'Guaranteed QoS' have explicit bandwidth guarantees and a 'Controlled Load' that ensures transmission packets even in overload situations without guaranteeing explicit numbers. IntServ is a fine-grained network architecture supporting QoS on a per flow basis. All routers need to support IntServ on the data path. Routers also need to maintain many state information.

2.1.6.4 Differentiated Services (DiffServ)

The IETF defined in [76] the Differentiated Services (DiffServ) concept controls QoS within the network using Differentiated Service Codepoint (DCP) in combination with per-hop routing behavior (PHB). DCPs classify certain packets into classes, without direct mapping of the QoS level. Only network edge routers are allowed to modify the TOC field in the TCP header to avoid abuse. Trusted boundaries are located between active network components (devices) and the network assigned packet data streams with best-effort per default.

Packet classifiers in DiffServ network architectures select IP packets in a traffic stream based on packet header information. Either the BA (Behavior Aggregate) Classifier, which uses DS codepoint only or the MF (Multi-Field) classifier, which selects packets based on the value of a combination of one or more header fields classifies the packets. Meters, Markers, Shapers and Droppers control the packet data flow at each hop on the path.

Differentiated Services is a schema for classifying application data flows and ensuring QoS. The Type-of-Service (TOS)-byte in the TCP header identifies the DiffServ level on a range between 0 and 7 ensuring interoperability between networks. Three bits are used for explicit marking of an IP packet. DiffServ is a coarse-grained network architecture supporting QoS on a per class basis.

2.1.6.5 Session Initiation Protocol (SIP)

The Session Initiation Protocol (SIP) as described in [77] is an application layer protocol developed by the IETF. SIP is a control protocol that can establish, modify, and terminate multimedia sessions (conferences) such as Internet telephony calls or multicast sessions. The design of SIP is based on the principles of the two most successful Internet protocols: Simple Mail Transfer Protocol (SMTP) and Hypertext Transfer Protocol (HTTP). SIP is a text-based protocol which exchanges messages in an offer/answer model, which is widely used to establish multimedia sessions in the domain of VoIP. Many IMS based applications in the Internet require the creation, management and termination of a session, where a session is considered to be an exchange of data between an association of participants. Users may be addressable by multiple names, may move between endpoints or may communicate simultaneously but in different media. SIP enables Internet Endpoints (User Agents) to discover one another and to agree on a characterization of a session they would like to share. The communication process of SIP is quite similar to the Hyper-Text-Transport-Protocol (HTTP) and works with requests and responses. The architecture of a generic SIP message has the following structure:

- Start-Line = Method (space) Request-URI (space) SIP-Version CRLF [one]
- Header = Header field name (:) header field value [multiple]
- Control Line Feed (CRLF)

- Optional Message-Body

The message body can be empty or it can contain a Session Description Protocol (SDP) [78] to negotiate session parameters. A SDP description consists of session-level information and media-level information and is text-based. Other body types are subject to future standardization or proprietary development.

2.1.6.6 Real Time Protocol / RTP Control Protocol

The Real Time Transport Protocol (RTP) [79] has been developed by the Audio-Video Transport Working Group of the IETF and defines a standardized packet format for delivering audio and video over the Internet. RTP is usually used in conjunction with the RTP Control Protocol (RTCP). The majority of the implementations of RTP use the unreliable UDP for data transport and RTCP to monitor transmission statistics and quality of service information. Both are widely used in the domains IPTV and VoIP. While RTP carries the media streams (e.g., audio and video), RTCP is used to monitor transmission statistics and QoS information. The majority of the RTP implementations are built on the unreliable UDP/IP. Sequence numbers and timestamps are placed in the protocol header to ensure a reordering at the receiver side. Captured multimedia data is compressed into frames with a suitable encoder. If the compressed frames are larger than the Maximum Transmission Unit (MTU), they may be fragmented into several RTP packets. If they are smaller than the MTU, several frames may be bundled into a single RTP packet. The sender may make changes to the transmission parameter, depending on the quality feedback received on RTCP.

2.1.6.7 Diameter Protocol

Diameter [63] approved in 2003 is a protocol designed by the IETF and is an improved version of the RADIUS [80] protocol. Diameter was selected for the IMS to perform AAA functions locally and in roaming situations. The term AAA has been traditionally used to refer to the following security functionalities:

- Authentication (verifying the identity of an entity),
- Authorization (allowing access or not to a resource) and
- Accounting (collecting information on resource usage for billing, auditing or cost allocation)

These three concepts are intimately linked and they provide the required protection and control for accessing a network, so that operators can bill the end-user for services used. Diameter works in a peer-to-peer fashion in comparison to RADIUS, which enables every communication endpoint to initiate an information exchange and is thus not limited to client-server communication. In comparison to RADIUS, Diameter supports secure transport over TCP and SCTP, is backwards compatible to RADIUS, has a modular structure and is extensible.

2.1.6.8 Application Layer Traffic Optimization Protocol (ALTO)

The ALTO initiative proposes a draft approach in [81] for enabling communication between Internet Service Provider (ISP) and network overlays to optimize traffic being generated by Peer-to-Peer (P2P) applications and transported over the ISP's infrastructure.

The Application Layer Traffic Optimization (ALTO) working group is the successor of the P4P initiative. ALTO first proposed an optimizing process for P2P networks. Classic 3rd Generation P2P networks - as described in 2.2.8 - form a logical P2P network overlay independent from the underlying physical network. The peering process between peers does not take the connectivity parameter or ISP SLAs into consideration. ATLO aims to compensate the drawbacks by creating dedicated network nodes - ALTO server - for aiding the peering process with network operator knowledge about the peers. Dedicated ALTO servers are required in each operator network, which has was not executed by all ISPs and therefore did not have the expected influence. Additionally P2P lost the interest of end users over time and Content Delivery Networks (CDN) became a more prominent alternative. CDNs provide geographically distributed efficient service data rate to the end user.

2.1.6.9 A Framework for Policy-based Admission Control

A conceptual Framework for Policy-based Admission Control is presented in IETF RFC 2753 [82]. The framework focuses on policy-based control over admission control using RSVP as an example of the QoS signaling mechanism. A client-server protocol is applied for communicating between a policy server (PDP) and its client (PEP). Only the framework and basic interactions are discussed, no protocol is specified nor additional mechanisms discussed. The PEP queries the PDP upon retrieval of a message (which requires a policy decision) by formulating a request for a policy decision. The PDP is expected to consolidate an adjacent LDAP, SNMP service for accessing a remote policy database.

2.1.6.10 Network Configuration Protocol (NETCONF)

The Network Configuration Protocol (NETCONF) standardized by IETF [83] provides mechanisms to install, manipulate, and delete the configuration of network devices. Four layers have been defined for NETCONF. The Content layer stores configuration data in the form of data models. The Operations layer structured in XML format for base protocol operations like get/edit/delete/lock/unlock, etc. The Message layer uses Remote Procedure Calls (RPC) in an XML format for method invocation. The Secure Transport Protocol layer supports SSH, TLS, SOAP/HTTP and provides a communication path between client and server.

2.1.6.11 Forwarding and Control Element Separation (ForCES)

The IETF working group ForCES [84] defines an architectural framework and associated protocols to standardize information exchange between the control- and data plane in a ForCES Network Element (ForCES NE). ForCES defines Network Elements (NE), Control Elements (CE) and Forwarding Element (FE). In comparison to the SDN concept, which strictly separates forwarding from control in different functional elements, ForCES allows each NE to consist of multiple NEs and FEs. A Network Element is therefore more complex and is controlled through a CE Manager and FE Manager - each managing the references Control or Forwarding Element(s).

2.1.7 Net!Works

Net!Works is a collaboration of 869 international partners (as stated in December 2012) including research organizations, network operator and vendors who have published a white paper [85] on Future-Network-Management naming research priorities and recommendations in 2011. The new envisioned network architecture should be capable of evolution and support for integrated services and Context-aware and Content-aware networking. Net!Works formulated recommendations for inclusion into the new funding schema FP8/Horizon2020 [86] of the European Commission work program based on current trends in services/applications and as key drivers in the evolution of networks towards future smart software-defined networks.

- R1) *'Future Network core must be universal in terms of efficient support of all access technologies with sufficient intelligence and cognitive features for autonomous yet stable and controllable operation.'* [86]
- R2) Future Network Architectures (first point) *'Unification and higher degree of visualization for all infrastructure systems: visualization of applications, services, networks, storage, content and resources as the means of enabling change from capacity concerns towards increased and flexible capability with operation control.'* [86]
- R3) Future Network Programmability and Elasticity *'Future Networks should have its architectures optimizing the capacity of network equipments based on service requirement and user demand.'* [86]

These definitions, design goals and recommendations of Net!Works are manifold and overlap in parts with the scope of this thesis.

2.2 Academic Research on QoS Management

The following subsections summarize related research on Cross Layer QoS control in NGN and FI. First, a report published by the European Commission outlining the requirements for ICT until 2020 is reviewed and QoS related requirements are derived. Furthermore, international research projects are listed in the following together with a list of academic publications and conferences on the topic of Cross Layer QoS control in NGN and FI. In addition Software-Defined-Networks and Network Virtualization are introduced and best practice implementations are presented.

Finally the software prototype OpenEPC of Fraunhofer FOKUS and TU Berlin is presented.

2.2.1 ICT for Smart City and Horizon 2020 by European Commission

The European Commission published the report STRATEGIC PRIORITIES FOR THE NEW FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION COVERING THE PERIOD 2014-2020 'Report of the Meeting of Advisory group ICT Infrastructure for energy-efficient buildings and neighbourhoods for carbon-neutral cities' [87, p16] under the umbrella of Smart Sustainable Cities with research topics suggestions for ICT. The main idea is to reduce energy drastically in the ICT domain to improve the carbon footprint of cities by moving to a more intelligent use of energy through enhanced efficiency. Research in the field of 'Guaranteed QoS, timely delivery, processing of key events', 'optimisation of connectivity and information transfer' is demanded explicitly.

2.2.2 International Research Projects

This subsection summarizes related work of international research projects on or with specific aspects on QoS optimization. These projects are namely MEVICO, iJOIN, G-Lab DEEP, FIWARE, MobileCloud-Networking and FISTAR.

FP7-ICT-214063 - SEA The 7th ICT Framework Programme (FP7) SEAmless content delivery project focuses on a Cross Layer Interfaces following an application-centric approach. In deliverable D2.3 [88] of the SEA context adaptation decisions only regard the application layer, a centralized adaptation control is therefore located at the application layer. Multi-source/multi-network streaming and adaptation has been targeted but not adopted in the Cross Layer approach.

All the adaptation actions will be taken at the application layer, exploiting proper information collected from the application as well as from the lower layers, and having a proper end-user QoS metric as the objective function to be maximized. Adaptation interfaces uses pre-encoded video to enable the delivery of different qualities. Multimedia streams encoded over H264/AVC with a number of layers are de-multiplexed at the source and combined into a single stream with improved quality finally.

The SEA project addresses on-the fly content adaptation by dynamically combining different content layers over multiple diverse paths or networks.

Mobile Networks Evolution for Individual Communications Experience (MEVICO) The EUREKA-Verbundsprojekt MEVICO [89] defines six building blocks for a traffic management architecture - the most relevant and innovative in deliverable 1.3 are the following. Traffic management of individual flows based on application type, user profile and other policy related information is to be incorporated within a microscopic traffic management block. Macroscopic traffic management is aligned in Deep-Packet-Inspection (DPI) and improves efficient usage of network resources by identifying flows using traffic patterns. Application supported traffic management optimizes system performance from the end user perspective without network element support. Capacity extension in high load situations is envisaged, but not further specified.

Managing access- and core network heterogeneity implies control and management of multiple co-existing fixed and radio network technologies. The architecture defined within the MEVICO project includes the heterogeneous fixed and mobile networks as CET/DWDM, IP/Ethernet/NG SDH and also different radio technologies sharing the same transport network, such as UMTS; HSPA, HSPA+, LTE, LTE-A, WiMAX and WLAN. In order to maintain heterogeneity in the network, an open standard layered network architecture for co-existing network technologies is suggested.

BMBF G-Lab DEEP The BMBF funded G-Lab DEEP project [22] concentrates on Functional Composition and Cross Layer Control Mechanisms with special focus on security. G-Lab DEEP is a phase 2 project of G-Lab and builds on top of the existing G-Lab infrastructure developed in phase 1. The G-Lab-platform is distributed physically among the partner institutes and is used for the evaluation of the developed (distributed) concepts. A revolutionary Internet design approach is followed by G-Lab DEEP instead of incremental enhancements of evolutionary approaches. The project addresses issues related to the Future Internet and the provisioning of appropriate experimental platforms in the academic environment, with an emphasis on current work in the G-Lab framework. The main focus of this project is to convey the requirements that result from a concrete application layer workflow to the network layer, innovative approaches, concepts and three prototypes as an outcome of a spiral project management development process. Innovative approaches, new concepts and three prototypes as outcome of a spiral project management development process have been developed and presented. One major outcome of the 3 years project is the mediator Cross Layer component [37, 90, 91, 92]. The ISO/OSI network layer is only condensed into the three layers of application, mediation and connectivity.

EU FP7 ETICS The EU ICT Economic and Technologies for Inter-Carrier Services (ETICS) project [93] aims at creating a new ecosystem of innovative QoS-enabled interconnection models between Network Service Providers allowing for a fair distribution of revenue shares among all the actors in the service delivery value-chain. To achieve these objectives, ETICS will analyse, specify and implement new network control, management and service plane technologies for the automated end-to-end QoS-enabled service delivery across heterogeneous carrier networks.

EU FP7 CONCERTO The FP7 ICT STREP project CONCERTO (Content and cOntext aware delivery for iNteraCtive multimedia healthcaRe applications) [94] aims at designing and validating several critical building blocks of telemedicine applications. The ultimate aim of CONCERTO is to provide a high Quality of Experience (QoE) for medics, which is a necessary condition for providing flawless medical diagnosing of the highest level of reliability. Network-aware application, context awareness, Cross Layer optimization and radio technologies such as LTE play an important role within the project. The main focus of the project lies on HTTP streaming with new concepts on the Medium Access Layer (MAC) for optimizing retransmissions, while maximizing QoE. Error correction, erasure recovery and scheduling are the main concern.

EU FP7 iJoin The Interworking and JOINt Design of an Open Access and Backhaul Network Architecture for Small Cells based on Cloud Networks EU ICT project iJOIN [95] addresses the challenge of sparse radio resources in (future) mobile telecommunication networks. One key idea is the substitution of few macro cells with multiple small cells, in order to utilize the available capacity more optimally. New challenges arise as inter cell communication increases - LTE/EPC over the X2 reference point. Basically the network becomes more flexible by deploying radio resources (eNB) on demand using RAN-as-a-Service. Finally a control and decision logic will dimension the network topology / network template graph, which is aligned to the Cross Layer Optimization paradigm presented in this thesis.

FI-PPP FI-WARE Project The Public-Private-Partnership flagship project Future Internet Core platform (FI-WARE) understands itself as follows:

> 'FI-WARE will deliver a novel service infrastructure, building upon elements (called Generic Enablers) which offer reusable and commonly shared functions making it easier to develop Future Internet Applications in multiple sectors. This infrastructure will bring significant and quantifiable improvements in the performance, reliability and production costs linked to Internet Applications - building a true foundation for the Future Internet. The project will develop Open Specifications of these Generic Enablers, together with a reference implementation of them available for testing. This way, it is aimed to develop working specifications that influence Future Internet standards.' [23]

All Generic Enablers expose a specific functionality provided by the FI-CORE platform and are aggregated into five different groups, namely Enabler Spaces. These are Cloud Hosting, Data/Context Management, Internet of Things (IoT) Services Enablement, Applications/Services Ecosystem and Delivery Framework, Security and Interface to Networks and Devices (I2ND). The 'Interface to Networks and Devices (I2ND)' defines an enabler space for Generic Enabler (GEs) to control and manage open and standard network infrastructures.

Four enablers had been defined in the scope of the I2ND at the time this thesis was written:

- Connected Device Interface (CDI) GE: Access device features and device capabilities independently from the handset manufacturer, the OS vendor or the specific software embedded into the device.
- Cloud Edge (CE) GE: An interface towards cloud proxies, service and resources.
- Network Information and Control (NetIC) GE: An interface towards heterogeneous (virtual) fixed and mobile network control (topology/QoS control and management).
- S3C GE: An interface towards underlying networks providing a unified and scalable control of the connectivity of the devices over heterogeneous access networks and core network technologies, transparent to the devices and to the services deployed on top.

Future Internet - Social and Technological (FISTAR) The ICT Integrated Project (IP) Future Internet - Social and Technological (FISTAR) [25] will establish early trials in the health care domain building on Future Internet (FI) technology leveraging on the outcomes of FI-PPP Phase 1. The plan of FISTAR is to become self-sufficient after the end of the project and will continue on a sustainable business model with several partners. In order to meet the requirements of a global health industry FI-STAR will use a fundamentally different, 'reverse' cloud approach, that is; it will bring the software to the data, rather than bringing the data to the software. FI-STAR will create a robust framework based on the 'software to data' paradigm. A sustainable value chain following the life cycle of the Generic Enablers (GEs) will enable FI-STAR to grow beyond the lifetime of the project. FI-STAR will build a vertical community in order to create a sustainable ecosystem for all user groups in the global health care and adjacent markets based on FI-PPP specifications.

FI-STAR will deploy and execute 7 early trials across Europe, serving more than 4 million people. Through the trials FI-STAR will validate the FI-PPP core platform concept by using GEs to build its framework and will introduce ultra-light interactive applications for user functionality. It will pro-actively engage with the FI-PPP to propose specifications and standards. FI-STAR will use the latest digital media technology for community building and will pro-actively prepare for Phase 3 through targeted elicitation of new partners using open calls.

Finally, FI-STAR will collaborate with other FI-PPP projects, through the mechanisms in place, by actively interacting with all necessary bodies. FISTAR is a phase two use case project that aims to validate the FIWARE Generic Enabler in specific use cases. One addressed goal of FISTAR is the integration of network resource control mechanisms for optimizing the connectivity of the eHealth service domain. A Generic Adaptive Resource Control (GARC) function is defined to address these challenges explicitly as it is stated in the Description of Work of FISTAR.

> ***'Technische Universität Berlin (TUB) will contribute to heterogeneous access network support and optimization for fixed and mobile (virtualized) networks and the attached radio devices. Fixed and mobile access- and core-network congestion control and optimized connectivity are targeted by TUB. A particular focus is on cross-layer service control paradigms between application- and network-layer for optimizing the connectivity according to application layer requirements'*** *[96]*

The optional GARC component resides in the network operator domain and aims to mediate on demand between application layer requirements and network layer capabilities.

EU FP7 ENVISION The EU FP7 project ENVISION [97] addresses Co-optimization of overlay applications and underlying networks mainly for P2P networks through the definition of a REST interface between Service Overlay Networks and the underlying physical network.

The comprehensive, media-aware and open Collaboration Interface between Network and Applications (CINA) presented in [98], aims to bridge the gap between ISPs and application overlays. CINA also goes further than the IETF ALTO approach and aims at optimizing application overlay networks with respect to the capabilities of the underlying networks and the participant end users. Multi-viewpoint coverage through combination of multiple streaming sources of different quality levels.

The CINA interface aims to improve content adaptation using scalable video codecs on the application layer; low-latency and high-capacity content dissemination; manipulation of distributed and streaming content such as the interpolation of multiple audio-visual streams from different viewpoints; exchange of live, multisensory, and contextual information between participants; and the discovery and navigation of distributed content, information and users.

Network services such as multicast groups, caches are used through the CINA interface to reduce total network load and improve content delivery for client-server and peer-to-peer networks. A functional 'overlay management block' takes end user bandwidth capabilities and access network into account for connection optimization. No user demanded QoS requests are supported. Applications need to use the CINA/ALTO interface, which requires the modification of existing applications. No backward compatibility is envisioned.

The CINA interface and functional components present a conceptual idea and early functional interface definition. No protocol extension to ALTO has been presented.

2.2.3 Relevant Conferences and Workshops on QoS

Publications and relevant conferences and workshops on QoS in NGN and FI are presented in the following.

IEEE/ACM IWQoS Workshop In 2012 the 20th edition of the IEEE/ACM IWQoS workshop continues the series of conferences and workshop addressing QoS in application-aware, admission control and design for Future Internet in addition to other topics [99].

The workshop series ContextQoS [100] addresses Context-aware QoS provisioning and management.

ITU-T Workshops on Next Generation Networks The ITU-T Workshops on NGN series aims to identify emerging developments in ICTs under the topic of Building Sustainable Communities. QoS for differentiated sources is explicitly part of the Call-for-Paper [101].

ITG-Fachausschuss 5.2 ITG-Fachausschuss 5.2 Kommunikationsnetze und -systeme [43] consists of several subgroups analyzing Future of Broadband Wireless, Fixed Mobile Convergence, Next Generation Mobile Networks, Architectures, Quality of Service among other topics.

Selected Items on Telecommunication Quality Matters ETSI hosts the workshop on Selected Items on Telecommunication Quality Matters (TC STQ) [102] discussing topics alike standardization relating to terminals and networks for speech and media quality, end-to-end single media and multimedia transmission performance, QoS parameters for networks and services and QoE descriptors and methods.

2.2.4 Software Defined Networks (SDN)

Resource sharing enables more efficient resource utilization and might result in cost savings. Virtualizing a network enables the operation of multiple protocols in parallel and independent of each other, providing a smaller closed virtual partition of a larger physical network, or enables security by providing access control by separating network entities.

Virtual Private Networks (VPNs) or Virtual Local Area Networks (VLAN) are widely used technologies for creating virtual overlays on top of physical transport networks.

VLAN as described within [32] is the concept of grouping different hosts to a virtual network topology, which is independent of the underlying hardware. The membership of an endpoint to a dedicated VLAN is software defined and not realized over physical links. All data traffic related to one specific VLAN is marked with the same VLAN-tag or 802.1Q header within the header of an Ethernet frame.

VPNs and VLANs separate and isolate network traffic in predefined virtual networks effectively, but are too inflexible to be managed dynamically. Configuration and management of data-link layer 2 and network layer 3 devices such as switches and routers have to be maintained with high level complexity.

The term Software Defined Networks (SDN) refers to the concept of separating control and data plane in the network. The separation within the layer enables external management and control of distributed lower layer transport functionalities. The theoretical concept of SDN has been implemented by multiple standardization organizations (ONF, IETF/IRTF, ETSI, ITU-T, IEEE, etc.) to create practical solutions (e.g. ONF OpenFlow, CISCO's OpenPK, IBM's DOVE, NEC's Programmable Flow, etc.).

Several working and discussion groups of the Open Networking Foundation (ONF) are covering various SDN related topics. The OpenFlow technology [103] introduced as an academic approach by Stanford University and now being specified by Open-Network-Foundation (ONF) [13] is a famous example for virtualizing networks, in order to run independent experiments on the same hardware environment by separating switching from control.

The OpenFlow concept changes the packet switching and routing behavior in traditional networks. This concept separates routing and packet forwarding by extracting the routing decision out of the switch and putting it into an OpenFlow Controller (OFC) (e.g. NOX [104]).

Figure 2.2 illustrates the main functional elements (OpenFlow Switch OFS and Controller OFC) and reference points (OpenFlow Channel) for an OpenFlow network.

The OpenFlow Switch functionalities are limited to pure packet forwarding. An SSL secured OpenFlow Channel transports OpenFlow Protocol (OFP) messages used for communication between OpenFlow Controller and OpenFlow Switch to request and signal routing decisions. Routing tables within OpenFlow Switches are provisioned for either static and predefined, or dynamic and on-demand for incoming packets.

OpenFlow enables networks to support traffic isolation, creates an open environment and flexible flow definition by individual flows, aggregated flows or post-IP protocol support. OpenFlow defines itself as an 'open standard to deploy innovative protocols in production networks' [105] and is Open Source available. Commercial Internet switches, routers and wireless access points are supported, which eases the setup of test infrastructures through backwards compatibility.

FlowVisor [106] is a special purpose OpenFlow controller that acts as a transparent proxy between OpenFlow switches and multiple OpenFlow controllers. FlowVisor supervises independent controller derivations assigning one single slice to each controller and provides network traffic isolation. In detail, FlowVisor intercepts, filters and modifies OFP communication between controller and switches.

SDN [107] focuses within SDNRG on areas of interest covering the classification of SDN models, relationship to work ongoing in the IETF and other SDOs, SDN model scalability and applicability, multi-layer programmability and feedback control systems, system complexity network description, as well as security.

The ITU-T Study Group 13 ITU (Future networks including cloud computing, mobile and NGN) [108] is standardizing FNs with the objectives of service, data, environmental and socio-economic awareness as part of the topic SDN. Completion

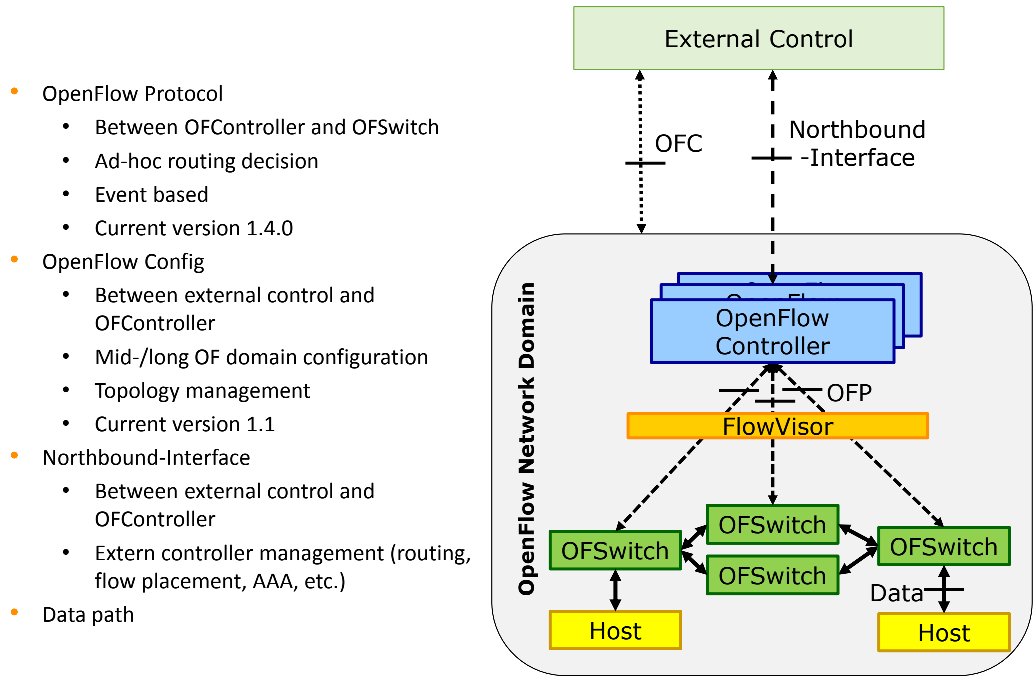

Figure 2.2: ONF Software Defined Networking Architecture

of standardization efforts to support network virtualization, energy saving for FNs, and an identification framework. Future plans include developing different facets of the smart ubiquitous network, requirements of network virtualization for FNs, framework of telecom SDN and requirements of formal specification and verification methods for SDN.

The Institute of Electrical and Electronics Engineers (IEEE) is about to start working on SDN as indicated during the IEEE SDN4FNS workshop in November 2013.

Urs Hoelzle (SVP Google) announced in [44] the use of OpenFlow for SDN at scale within Google's two operational networks: (1) Internet-facing-backbone (user traffic) and (2) data center-backbone (internal traffic) of Google. The selection of SDN by Google was motivated by enhancing security and reliability through centralizing control and management while improving backbone performance and reducing backbone complexity together with costs in parallel.

OpenFlow protocol version and OpenFlow Config protocol version have been standardized by ONF. Both have the largest market share and influence at this point in time, since most vendors support at least OpenFlow as part of their portfolio.

2.2.5 Network Functional Virtualization (NFV)

The initiative driven by ETSI NFV aims to transform the way in which network operators design networks by evolving standard IT virtualization technologies. Software is separated from the dedicated hardware of network functions and isolated in Virtual Network Functions (VNF). Those NFVs are deployable on Commodity Off The Shelf (COTS) servers dynamically and demand driven. This fact enables more flexibility in terms of geographical placement, network dimensioning and autonomous provisioning to gain massive cost savings. New challenges and limitations occur on the other side in terms of security, complexity and interoperability as discussed in two ETSI NFV whitepaper [14, 16].

2.2.6 Open-Evolved-Packet-Core (OpenEPC) Toolkit

The OpenEPC toolkit developed by Fraunhofer FOKUS and TU Berlin, which adopts large concepts from the 3GPP EPC standards, represents an all-IP architecture permitting the research and the development of different wireless applications in a real wireless environment. For this matter, OpenEPC includes the mechanisms for connecting to different access networks and the communication interfaces to the various service platforms, offering the most suitable connection for the various services in terms of access network selection and of resource adaptation to the current network conditions [109].

Though its modular structure, the OpenEPC toolkit enables the fast deployment of test network architectures in various combinations to meet the requests from the research community. Through its policy and charging control architecture, the subscriber and mobility management mechanisms and through the easy interconnection with various access networks and application platforms, OpenEPC encompasses the complete spectrum of the wireless research enabling the further prototyping of core network enhancements.

2.2.7 Books, Journals and Conference Proceedings

Academic work on QoS control and Cross Layer approaches have been presented in publications. The most important and most directly related to this thesis are covered in this subsection.

QoS-routing with Systematic Access (Q-OSys) presents a concept for QoS routing in future Internet consisting of dedicated Q-OSys-capable ingress- and egress-routers. Q-OSys pre-reserves a fraction of the available QoS resources per router in advance during the initialization phase using RESERVE messages. QoS is measured End-to-End using metrics as Peak-Signal-to-Noise-Ratio (PSNR), Structural-Similarity (SSM), Video-Quality-Metric (VCM) and Mean-Opinion-Score (MOS). The concept is validated through an evaluation [110].

The authors of [111] give an overview of ITU-T NGN QoS control and provide a state-of-the-art section, which covers related standardization activities on QoS control.

In [112] Kumwilaisak et al present a local QoS interaction between source video encoder module, Cross Layer QoS mapping through feedback channel and link layer adaptation module. The authors assume that fading, time-varying and non-stationary characteristics of the wireless channel can be modeled by a discrete-time Markov model. The presented Markov model outlined as a concept and validated by a simulation.

In Chapter 1 of the book [33] Cross Layer Composition is presented as a concept for bridging the gap between the application- and network-layer through creating awareness of each other by applying service-oriented concepts to networking for enabling direct control message exchange.

An extensive State of the Art on programmable networks is given in [113].

Fotis Foukalas et al. outline Cross Layer design proposals for Wireless Mobile Networks in [10]. An elaboration of the system design points out the different placement option for the Cross Layer Optimizer as part of the network layer or as an external centralized or distributed entity.

G. Carneiro et al. present a Cross Layer model in [11] for optimizing QoS in mobile networks. Wireless link adaption is completed using Transport, Routing and Link Layer mechanisms such as Automated Repeat Request (ARP), Link Layer Control (LLC) and Bit Error Rate (BER) for adjusting flows. An external control model is regarded as being layer independent.

S. Khan et al. introduce a Cross Layer Optimization model in [12] that operates vertically to the layer stack, which are network, data link, and physical layers. The CLO model aims to maximize the video quality perceived at the end user, which is measured as Peak Signal-to-Noise Ratio (PSNR). The CLO model has no interface towards the end user device nor the service for retrieving application layer parameters. Therefore video source rate and other session related information are taken as assumed.

V.T. Raisinghani et al. present ECLAIR as a CLO model in [114] which includes feedback mechsnisms for system optimizations. The ECLAIR CLO model consists of two functional modules. A tuning layer (TL) for each layer provides an interface to read and update protocol data structures. Protocol Optimizer (PO) contains Cross Layer feedback algorithms and interact with TLs to optimize the protocols.

2.2.8 Peer-2-Peer Technology Evolution

Peer-2-Peer (P2P) technology is referred to as overlays for efficient and scalable information exchange. The last P2P networks are considering Cross Layer techniques for enabling network-awareness to the P2P network. Therefore P2P technologies overcome the scalability challenge of fixed Content-Delivery-Networks (CDN) by distributing the roles from the classic 1:1 server:client to a broader N:M communication model among the participants (peers). Static files or dynamic live-streaming multimedia applications disassemble a stream into numbered chunks, which are distributed among a set of active P2P streaming clients (tree or swarm for push and pull models) [115]. Peers within one swarm share the chunks until every participant receives a full set of chunks to be assembled into a complete copy of the initial (subset) stream. The control and management of the communication between peers of a swarm are defined in specific P2P algorithms. Many P2P algorithms are based on Distributed-Hash-Tables (DHT), which spread peers and pointers to content or identifiers at a limited numerical interval, which is in turn used as an address book to map content identifiers to peers. The most relevant P2P algorithms are grouped into four generations in historical order 1) Centralized index server approaches, 2) Flooded requests model, 3) Distributed Hash Tables (DHT) and 4) Next Generation P2P: Streaming Solutions, which particially enable network-aware services.

The first generation is characterized by the centralized directory model that Napster introduced in 2001. The second generation is characterized by Gnutella [116] (2000), Kademlia [117] (1999), Kazaa (2001). The third generation is characterized by Chord [118] (2001) and Content Addressable Network (CAN) [119] (2001), Tapestry [120] (2004), Pastry [121] (2001). The fourth generation is characterized by hybrid tree-based P2P topologies such as NNodeTree [35, 36]. The P4P [122] approach optimizes the connectivity graph between peers, through aggregating peers into a swarm based on their network operator association and geographical distance. The point of presence (PoP) is taken as one parameter of the P4P algorithm on grouping peers. Network operator and content provider collaborate in supporting a new components such as iTracker or ALTO server [81] that support dividing traffic control responsibilities between service provider and network operator and also allows incrementally deployable and extensible P4P.

2.3 Industry Driven Solutions to QoS Control

This section outlines industry driven solutions and products related to the thesis' scope and Cross Layer optimization as well as QoS control.

Open Service Access and Parlay X Open-application-programmable-interfaces (OpenAPIs) have been specified and standardized by multiple initiatives in parallel for accessing and controlling underlying network capabilities in order to improve or enhance existing communication features.

The main standardization initiatives are Tele-Management-Forum, Java Community Process (JCP), Open Mobile Alliance (OMA) and 3GPP.

Tele-Management-Forum (TMF) initiative proposes a Tele-Management-Forum-Service-Delivery-Framework (SDF) including Business Process Framework (eTOM), Information Framework (SID) and Applications Framework (TAM) management solutions. These encompass Service Problem Management, Inventory, Security, Fault Management, Policy Management, Performance Management and Expedited Interfaces.

Java Community Process (JCP) Java Community Process (JCP) is the mechanism for developing standard technical specifications for Java technology producing

Java Specification Requests (JSRs). JCP standardizes SIP Servlet 1.1 specification JSR 289 [123]. The JSR 281 SIP servlet container is aligned on the HTTP-Servlet container. Where the mapping of Java-methods to HTTP-request-methods is defined in a web.xml, the SIP-servlet-container uses sip.xml for this mapping. An application server hosts one or many servlet container, which in turn hosts and/or manages the life-cycle of individual services. An example of an Open-Source SIP servlet container is Java SailFin/Glassfish [124].

Open Mobile Alliance (OMA) standardizes Next-Generation-Service-Interfaces (NGSI), OMA-Service-Environment (OSE), OMA-Service-Provider-Environment (OSPE).

3GPP standardizes Service-Capability-Interaction-Manager (SCIM), which orchestrates service delivery among SIP application server platforms within the IP Multimedia Subsystem architecture.

OSA/Parlay APIs Open Service Access (OSA) Parlay is an open Application Programming Interface (API) for application access to telecommunication network resources. The OSA/Parlay technology supports secure, measured and billable interfaces towards telecommunication network capabilities with IT applications. OSA/Parlay APIs are network vendor and operator independent, and applications can be hosted within the telecommunication network operator's own environment (data centers), or by external third party service providers.

Part 17 of the Stage 3 Parlay X Web Services [125] specification for OSA addresses Application-Driven (ADQ) [125, 126] and is specified by 3GPP. The key idea is the specification of an open, standardized and network-independent interface that enables application developers to make use of network functionality such as QoS. The QoS control functionality is thereby exposed through a REST Web Service. ADQ enables applications to request pre-defined QoS features for a certain IP connection within the operator controlled network.

Rich Communications Services (RCS) and Joyn The specification of Rich Communications Services (RCS) [127] marketed as joyn is driven by GSMA. The evolution of RCS took place in four stages beginning with release 1 until release 5 at the end of 2012. RCS can be seen as an expression of the intention of the telecommunication domain (device manufactures, network operator and service provider) to stop the continuous loss of influence within the application domain to 3rd-Party Over-The-Top (OTT) service providers. Services that are supposed to be offered in RCS are already available through OTT and most of them have a broad user base. The telecommunication domain invests a large amount of effort to support reliability and interoperability in RCS in comparison to (nearly) free, isolated and non-interoperable OTT service features.

RCS is based on IMS services and RCS in release 5.1 (August 2012) contains Standalone Messaging, 1-2-1 Chat, Group Chat, File Transfer, Content Sharing, Social Presence Information, IP Voice call, Best Effort Video call, Geolocation Exchange, network based blacklist and Capability Exchange based on Presence or SIP

OPTIONS as standardized functionalities.

RCS is either embedded natively into the mobile device operating system or is downloadable. RCS release 5.1 is supported by the main vendors but not by Apple at the time this thesis was written. RCS aims to charge the user, but it has not yet made official, in which way the charging will be carried out.

One aspect of the reliability of RCS is QoS, but QoS and network-awareness is not supported at the point this thesis was written. All-IP devices rely on an always on connection for push notifications and service pull. Lower layer protocol notification mechanisms are also not used for savings in energy consumption or aggregating application layer signaling and data transport.

Skype The service Skype [128] has been gaining in popularity due to its royalty-free Skype-internal multimedia communication. Skype is adaptable to network condition changes by adjusting the service bit rate for voice and video according to the available bandwidth through changing the CODEC dynamically. Skype is a non-Open-Source closed product, encrypts its data traffic and has to be analyzed due to back-box-tests. In [129] the aggressive Forward-Error-Correction (FEC) of Skype is analyzed by applying artificial packet-loss and delay on the connection between two Skype instances in an isolated network. Skype transports the video data over UDP relaying on best-effort Internet and adjusting the video parameters such as sending rate, FEC redundancy, video rate and frame rate using a TCP feedback loop channel. Skype is a proprietary software, details on coding and network transmission algorithm are not available to the public. The common practice for analyzing proprietary closed software is blackbox testing in an isolated and controlled network environment as presented in [130] for Skype. The algorithms in Skype are able to adapt the bandwidth demands on the available network resources reactively.

OPENET The OPENET Policy and Charging Control introduces product enabling subscriber engagement to monetize data traffic with a finer grain. Tiered price models are offered to customers, who are enabled to select real-time controlled device and data plans suitable to their demands.

Adaptive-Bit-Rate (ABR) streaming over HTTP Delivering video over IP fixed and mobile IP networks started in the 1990s with IPTV mainly based on Service Delivery Platforms enabled by SIP and IMS. IPTV is controlled by network operators and service providers and enables non-linear television over IP in parallel to classic linear television broadcast technologies such as Digital Video Broadcasting - Terrestrial (DVBT), cable, etc. Non-linear television driven by Video-on-demand enables the user the control the video actively using start, stop, pause and timeshift functionality. Network operators and service provider independent Over-the-top (OTT) service providers offer multimedia Adaptive-Bit-Rate (ABR) streaming over HTTP. In order to maintain a good Quality of Experience, the delivery protocol needs to be able to dynamically switch the bit rate with no interruption in playback or action by the user. Video is encoded in several distinct bitrates on server side and is sliced up into chunks of a size between two or ten seconds. Each chunk is synchronized on the iFrame. Clients are enabled to switch between different quality levels of a stream by altering a playlist dynamically. Chaining the playlist actively and benefiting from lower or higher QoE in turn does not affect the active HTTP TCP connection. Famous examples are, in alphabetical order: Adobe (R) HTTP Dynamic Streaming [131], Apple HTTP Live Streaming [132], Dynamic Adaptive Streaming over HTTP (DASH) [133] and Microsoft IIS Smooth Streaming [134].

2.4 Evaluation and Taxonomy

All related work presented in this chapter concerns main standards and technological trends in Service Control Mechanisms (SCM) and QoS Architectures in NGN and FI. These SCM differ in multiple aspects, which are in the following used to characterize and compare these approaches.

Table 2.1 aggregates parameters on most ISO/OSI layers, which affect QoS control. A 3GPP telecommunication system such as EPS in combination with IMS as a common infrastructure for today's NGN has been selected as reference for this analysis. The first column represents the instance in focus at this stage of the analysis. The second column characterizes the parameters that are controlling the instance. These parameters are further divided into parameters with read- and/or write-access. Parameters having read access might be used as input for the policy decision process. A policy evaluation might have an impact on parameter having write access for adjusting the system accordingly using mechanisms identified in the following column. The final block identifies metrics used for characterization of the parameter in column two.

The most pragmatic distinction of the QoS approaches is the scope and the layers which are affected such as access-, edge- and/or core-network or nothing at all. A simplification of the ISO/OSI layer model consisting of access-, connectivity-, session-management- and application layer is used in the following. All four presented layers might consist of further layers and/or functional blocks as well.

Furthermore the presented QoS approaches can be distinguished in the way, in which the three main aspects of the QoS control process are covered.

1. An internal or external cause invokes the QoS control process. Either sense, monitor or manual interaction triggers this event.

2. The cause of the event is analyzed, one or more policy rules influence the decision making process that formulates an evaluation statement. Policy-Decision-Point (PDP according to 3GPP) covers these individual steps.

3. The evaluation statement is enforced through a Policy-Enforcement-Point (PEP according to 3GPP) and its resulting effect might be monitored optionally.

Instance	Parameter	Mechanisms	Metrics
Application Layer	CODEX, Frame rate, Bit rate, Resolution, FEC, RTCP packet-loss, App-video-buffer	SIP parameter negotiation	Video-stalling, MOS, E-model
Transport Layer	TCP Congestion, Header Compression, TCP Window Size, TCP Packet-loss	MPTCP	Retransmissions
Network Layer	SDF QCI, bearer, packet-drop, queue buffer size	Rate limitation, Traffic shaping, TE, SIPTO, Handover, IntServ, DiffServ, ECN, RTO, Routing, Flow placement	QoS Level
Data Link Layer	ARQ, FEC, MTU, FDMA, TDMA, CDMA, Cell-capacity, Cell-utilization	RRC, Frequency boundling, Larger MTU, MTU Path discovery, 802.11 rate adaptation	Frame Error Rate
Physical Layer	Signal Strength, latency, jitter, throughput, Transmission power	Modulation	Bit Error Rate (BER)
End User	Priority Level	Based on subscription	MOS, Perceived QoE
Terminal	Display resolution, Access network support, Energy level, RAM, CPU, HDD	Operating System, App	System status
Context	Location, Date, Time, Context information	TDF, MME, HSS	GPS-Coordniates, Tracking-Area, CellID

Table 2.1: Taxonomy of QoS Architecture Parameter in NGN and FI

In addition, the type and number of supported heterogeneous access networks is one criteria for differentiation among the different SCM approaches.

DSL Forum BRAS/DSLAM, PacketCable CMTS, ETSI RACS, ITU-T RACF, 3GPP IMS, EPC, PCC and MTC define similar PDP and PEP in their QoS architectures. The most relevant QoS architecture is defined by 3GPP, on which covers most of the access- and core network technologies. Packet-Cable aligned its QoS architecture on 3GPP reference points Rx and Gx while using the SIP signaling protocol.

Most of the presented approaches perform greedy local decisions by granting or revoking specific QoS requests based on local resource availability. The main QoS architectures of ETSI, ITU-T and 3GPP enable roaming over interoperable interfaces towards remote domains for global operations. Other approaches (CableLabs, DSL Forum) perform only local decision making limited to a single domain. No approach includes historical decisions or signaling or data traffic patterns from the history of the network operation.

Characteristics of the individual Service Control Mechanisms (SCM) and QoS architectures have been compared in a single Table 2.2. Three main groups of characteristics have been identified and measured in five categories of (– –) not supported, (-) weak supported, (o) average, (+) supported, (++) very well supported Those characteristics are grouped as followed into the categories: a) general, b) support and c) architecture.

The first group includes general aspects of the approaches. The term granularity defines QoS control applicable on a per user, flow, service and/or device level. Extensibility describes the level of flexibility in which new services can be added next to existing services and in which services can be combined together in a service mesh-up. Openness describes the availability and ability of an open interface for external 3rd Party control. The support of roaming between different operator networks is analyzed. Another aspect is the support of network-awareness or non-network-awareness towards services. The last point describes the grade of dynamics in which changes in a policies effect the underlying system. This might be real-time or postponed to the next service invocation.

The next functional block on support contains characteristics as the usage of location information for policy decisions and the support of user demanded QoS requests. Another factor is the seamless QoS support in which an equal level of QoS in the source-network is supported in the target-network during vertical handover.

The last functional block analyzes the architecture and its characteristics. These functionalities consist of but are not limited to a Policy Decision Point, Policy Enforcement Point, Monitoring Functionality, Control Interface, 3rd Party Support, External Control and Policy Model Definition. The architecture and its functional block are either distributed or centralized. The support of a monitoring and events reporting functionality is discussed. In addition, dynamical or real-time situation-awareness in comparison to static pre-provisioning of QoS policies is analyzed. Level of customizability distinguishes between full operator controlled environments or the ability to use external (user or service provider) control and management.

Characteristics	Packet-Cable	DSL-Forum	ETSI	ITU-T	3GPP
QoS Granularity	-	-	-	-	o
Roaming Support	−−	−−	+	+	+
Event Notification	-	-	-	-	+
Network Awareness	+	+	-	-	+
Flexibility	o	o	o	o	+
Heterogeneous Network Support	-	-	+	+	+
Location	-	-	+	+	+
User Demands	-	-	-	-	-
Seamless QoS	-	-	-	-	-
Device Capabilities	-	-	-	-	-
Policy Decision Point	+	+	+	+	+
Policy Enforcement Point	+	+	+	+	+
Reporting Functionality	-	-	-	-	+
Control Interface	+	+	+	+	++
3rd Party Support	-	-	+	+	+
Adaptability	-	-	-	-	o
Extensibility	-	-	o	o	+
Openness	o	o	++	++	++
Evaluation	-9	-9	-1	-1	+12

Table 2.2: Taxonomy of QoS Architecture Features in NGN

Figure 2.3 outlines the main standards and technological trends in Service Control Mechanisms and QoS Architectures in NGN and FI into a simplified ISO/OSI network layer model. Four main categories have been identified to aggregated service control mechanisms and functional blocks. This figure names the most relevant approaches and positions them for comparison layer wise. For simplicity's sake neither interfaces between components of a single approach (e.g. BRAS and DSLAM) nor interfaces between two or more approaches (e.g. Packet-Cable and IMS) have been shown. These interconnections between technologies are left out for simplification within the figure and are explained within the individual State-of-the-Art section in more detail.

3GPP solutions such as the Evolved Packet Systems span over the two rows of Access and Connectivity with LTE and EPC. Session control in 3GPP has been identified with SIP based IMS and Policy Charging and Control functions. Application control is realized in 3GPP with OpenAPIs such as Parlay, SIP application

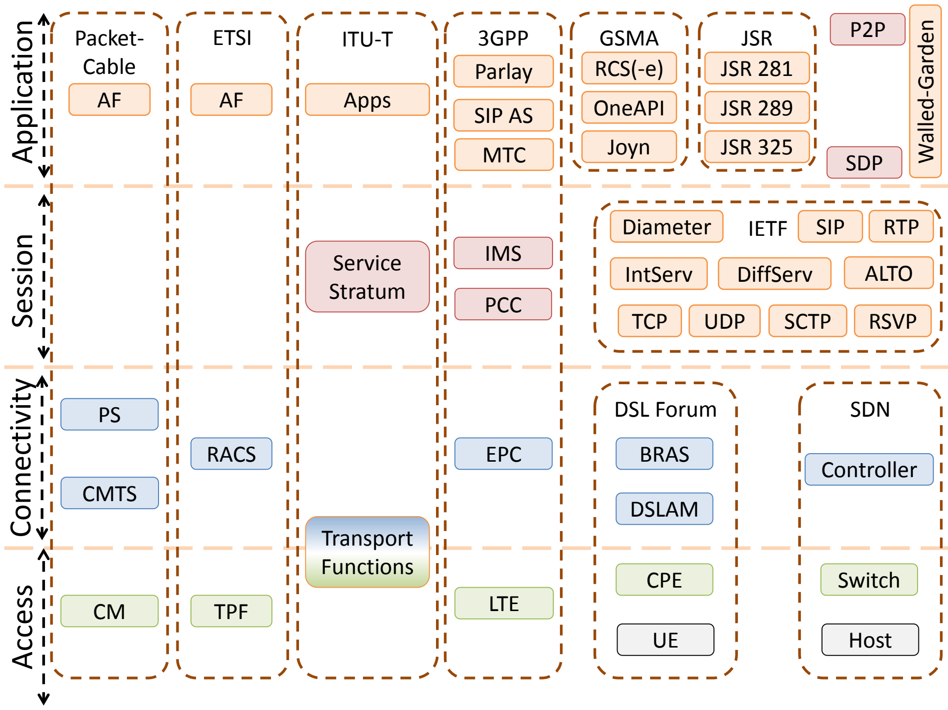

Figure 2.3: State of the Art on Service Control Mechanisms and QoS Architectures in NGN and FI

server or Machine Type Communication control platforms.

Software defined networks in comparison span only over the Access and Connectivity as they have a smaller feature set with controller, switches and hosts in their architecture.

A set of protocols (mainly standardized through IETF) has been analyzed and is aggregated in the row for Session control.

At the time this dissertation was written, there is already a lot of material published on Quality-of-Service control but only very limited work on flexible Cross Layer QoS control. This work differentiates itseld from other existing work in the following points:

- Generic access network support: 3GPP and non-3GPP, fixed, mobile and wireless, NGN and FI.
- Enable service-aware networks: Enable service data rate adjustments based on network technology performance characteristics and dynamic network load situations.
- Enable network-aware services
- Support active and passive application-layer QoS requests
- Enable user-demanded QoS requests

- Flexibility in QoS provisioning

2.5 Summary

This section outlines and discusses related work in academia and industry, which influences QoS control in Next Generation Mobile Broadband Networks and the Future Internet. Key standardization activities including ETSI, PacketCable, DSL Forum, ITU-T, 3GPP and IETF are presented in the first subsection. The second subsection discusses several academic work, which is followed by a third subsection presenting international research projects namely BMBF G-Lab, EU FI-WARE and EU MobileCloud-Networking that cover QoS control in heterogeneous access- and core-networks. Industrial products addressing (Cross Layer) QoS control are presented and discussed in subsection four. Finally an extensive evaluation compares the presented related work.

The following section presents the requirement analysis of this thesis.

Chapter 3

Requirements Analysis and Engineering

The previous chapter discussed the *State of the Art* on Cross Layer Optimization including relevant standards, international projects, commercial products and related research activities. This chapter elaborates and discusses the most relevant functional and non-functional requirements on Cross Layer service control.

The name of this chapter has been chosen as *Requirements Analysis and Engineering* to point out first the initial analysis and furthermore highlight the process of formulating, documenting, maintaining and refining the requirements on Cross Layer service control over the time of accomplishing this thesis. Afterwards, the here identified requirements are compared with the related work from the previous chapter. A gap analysis evaluates the requirements against the related work. Finally, the identified requirements will be taken into the architecture specification phase of the following chapter.

3.1 Sources of Requirements from (Inter)-National Institutions

This section characterizes related use-case scenarios in today's networks. Different stakeholders such as end user, customer, service provider, device manufacturer, network operator and government perspectives have been taken into consideration.

3.1.1 European Commission

The European Commission [135] published the report STRATEGIC PRIORITIES FOR THE NEW FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION COVERING THE PERIOD 2014-2020 'Report of the Meeting of Advisory group Information and Communications Technology (ICT) Infrastructure for energy-efficient buildings and neighborhoods for carbon-neutral cities' [87, p16] under the umbrella of Smart Sustainable Cities with research topics suggestions for ICT. The main idea of ICT for Smart City and Horizon 2020 by European Commission is to reduce energy consumption drastically in the ICT domain to improve the carbon footprint of cities by moving to a more intelligent use of energy through enhanced efficiency. Challenges and opportunities have been realized and research in the field of

> 'Guaranteed Quality of Service (QoS), timely delivery and processing of key events [135]'

as well as

> '**optimisation of connectivity and information transfer** [135]'

is demanded explicitly.

The 7th Framework Program of the European Union formulates Challenge 6 in the call text for ICT on low carbon economy as follows.

> *'**Data Centres in an energy-efficient** and environmentally-friendly Internet. This addresses technologies and associated **services to monitor energy consumption and automatically optimise** power, cooling, computing, storage, and data transmission operations in function of energy consumption, environmental impact and cost policies.'* [135, p, 67ff]

3.1.2 Bundesnetzagentur

The annual report of Bundesnetzagentur [1] in 2012 [136] includes aspects on future proved and high performance networks. The report includes the following statements:

[1]The responsible regulatory authority for Germany, which controls (next to others) the telecommunication sector.

Efficient Capacity Usage
Grows in bandwidth demand on mobile radio telecommunication networks.

Net Neutrality
Ongoing discussions in regulatory bodies such as the Body of European Regulators for Electronic Communication (BEREC) debate the question on **whether and how selected traffic differentiation can be applied to the growing data traffic**.

3.1.3 Network Neutrality Debate

The term 'network neutrality' (net-neutrality) is discussed on service usage from an end user perspective. Different stakeholders such as end user, network operator, service provider, content provider and legislative bodies have individual viewpoints and interests in this active debate. Three main aspects have to be taken into account with regard to this thesis.

Firstly: Net-neutrality between end users and Telecommunication Service Provider (TSP). The openness has been one of the major success criteria of the Internet, which need to be ensured further on. Each end user should have the same minimal QoS guarantees for a connection.

Secondly: Net-neutrality between different end users. 10 percent of the mobile subscribers generate 50 percent of the total data traffic according to CISCO traffic statistics. In order to ensure fairness, all end user of the same subscription class have to have the same connection quality. Fairness needs to be provided to ensure the balance of available and claimed resources for all subscribers.

Thirdly: Service differentiation. Due to the convergence of networks and the trend towards All-IP, all data is transported as packets over the mobile network. Quality of Services classes have to be defined, which correlate to the type and classes of services. 3GPP specified nine Quality of Service Class Identifiers (QCI) to generalize those different traffic classes consistently: signaling, real-time and non-real-time IP data traffic. In contrast to the first point, service differentiation is required to ensure the correct and reliable behavior of the transport network even in overload situations.

3.1.4 Standardization Organization Requirements

This subsection outlines requirements announced by international standardization organizations (SDOs), which are valid for this thesis.

3.1.4.1 3rd Generation Partnership Project (3GPP) Feasibility Study

Increased IP data and Diameter signaling traffic caused by the large number of devices, numerous applications and bandwidth suffering multimedia streaming services and fast technology product cycles, challenge today's networks. Access- and core network congestion handling is a hot topic of discussion at industry conferences [2, 3] and in standardization activities of 3GPP especially in context of 3GPP Policy Control and Charging (PCC) [4].

In addition three Feasibility Studies (FS) are currently analyzing impact, challenges and approaches on access- and core network congestion handling.

These are 3GPP FS:

- *'User Plane CONgestion management use cases and requirements'* (UPCON) [5]
- *'Study on Core Network Overload solutions'* (CNO) [6]
- *'Study on Application specific Congestion control for Data Connectivity'* (ACDC) [7]

Seven use cases have been defined as part of FS-UPCON for user plane traffic congestion in the RAN. The scenarios take parameters such as subscription of the user, the type of application, the type of content into account, but leave user demanded QoS and context out of scope. The level of granularity for identifying an application is rather high in comparison to the dynamic user initiated approach of this thesis, in which on demand QoS requests are realized next to static user profile information, as well.

The following requirements have been identified in the analysis of the use-case scenarios [5] challenged by user plane congestion:

- Flexible user demanded QoS requests should be supported.
- Application layer requirements should influence QoS control.
- The system should support network-aware services and service-awareness to networks. 'The system shall be able to identify, differentiate and prioritize different applications based on the QoS attributes of their communications'.
- The system should assist the network operator in controlling their network.

3.1.4.2 ITU Telecommunication Standardization Sector (ITU-T)

The Study Group (SG) SG13 established the 'Focus Group on Future Networks (FG-FN)' in January 2009 to share the discussion on Future Networks (FN) and to ensure global common understanding about Future Networks with collaboration and harmonization with relevant entities and activities. The FG successfully completed its work in December 2010 after two years.

General requirements have been formulated within the work of SG13 as recommendations for Future Networks as objectives and design goals in ITU-T Y.3001 (2011). The most relevant requirements for this thesis have been cited in the following:

> *Localization and Optimization. 'The Future Networks should support* ***localization and optimization of the signaling and data paths.****'* [137]

> *Programmability. 'The FN should support **programmable and re-configurable switches and routers and methods for managing those**.'* [137]

> *Service Awareness. 'Service awareness should be enabled for the FN. Therefore, Virtual Service Networks (VSN) should have specified parameters in terms of **capabilities and features exposed through virtualized and federated ICT resources as well as programmed with network services**. FNs are recommended to provide services whose functions are **designed to be appropriate to the needs of applications and users**. The objective Service Awareness includes service diversity, functional flexibility, virtualization of resources, **network management**, mobility and reliability and security.'* [137]

> *Security. 'FN are recommended to enable users to access desired data safely, easily, quickly, and accurately, regardless of their location.'* [137]

> *Network Optimization. 'FNs are recommended to provide sufficient performance by optimizing network equipment capacity based on service requirement and user demand. FNs are recommended to perform various optimizations within the network with consideration of various physical limitations of network equipment. The appearance of various services with different characteristics will further widen the variety of requirements among each service. For this reason, **FNs should optimize capacity of network equipment, and also perform optimizations within the network with consideration to various physical limitations of network equipment**.'* [137]

3.1.4.3 ISO/IEC JTC1 SC 6

The International Standardization Organization (ISO) addressed the importance of Future Network in ISO/IEC JTC 1/SC 6 telecommunications and information exchange between systems. In particular the TR 29181-1 [138] highlights the problem statement and requirements in Future Networks.

General requirements derived out of TR 29181 include but are not limited to: **mobility, heterogeneity, Quality of Service (QoS) support, re-configurability, context-awareness, manageability** (in an unsorted order).

ISO also defined in ISO/IEC 8348 [139] the reference model of Open Systems Interconnection (OSI). The OSI Reference Model (ITU-T Rec. X.200 | ISO/IEC 7498-1) subdivides the area of standardization for interconnection into a series of layers of specification, each of a manageable size. Functionalities are aggregated into layers, which communicate over well defined interfaces to the adjacent layer above or below.

3.1.4.4 Requirement Definition of ETSI on Evolved Packet System (EPS)

ETSI formulated service requirements for the Evolved Packet System (3GPP TS 22.278 version 8.7.0 Release 8): in [140] as part of the TS 122 278 V8.7.0.

> *'It shall be possible for the Evolved Packet System to maintain end-to-end QoS without modification when the terminal moves from one access system to a new access system, and the new access system supports the required QoS.'* [140]

QoS support for vertical handover between heterogeneous access networks are only supported to a limited degree.

> *'It shall be possible for the Evolved Packet System to* ***change QoS****, when the* ***terminal moves from one access system to a new access system*** *and the new access system can not provide the same QoS as the old access system or the new access system can provide higher QoS.'* [140]

> *'The Evolved Packet System shall provide for session mobility and* ***session adaptation to terminal capabilities, user preferences, subscriber priorities, network conditions and/or other operator-defined criteria****. Session adaptation shall be under the control of the operator.'* [140]

3.1.4.5 ETSI ISG Network Functions Virtualization (NFV)

The new established ETSI Industry Specification Group NFV will develop requirements and architecture for virtualization of various functions of telecommunication networks.

The reduction of operator CAPEX and OPEX through reduced equipment cost have been defined as requirements for new network technologies a set of initial goals. The following requirements are related to this work:

Energy awareness. Reduced power consumption. **Economic efficiency.** Reduced time-to-market to deploy new network services. **Improved RoI** Faster return on investment from new services. **Flexibility and Elasticity** Greater flexibility to scale up, scale down or evolve services.

3.1.4.6 Open Networking Foundation (ONF)

The Open Networking Foundation was formed in March 2011 and consists of major network operators and equipment vendors. The aim of ONF is the promotion of SDN and its standardization among all ONF members. Requirements on Software Defined Networks have been derived out of white papers [141] and standardization documents [13, 142].

Open Networking. The reluctance to experiment with production traffic emerged out of the new role of networks, which have become more and more critical infrastructures over the last decades.

Flexible control. Network equipment and protocols are widespread deployment and their management remains closed and static. Ossification of the network should be opposed through the introduction of open but controlled management interfaces. Closed networks are a barrier for innovative and disruptive ideas in terms of protocol and routing. The ONF fosters the promotion and acceptance of SDN through open standards development.

3.1.5 Net!Works White Paper

The Net!Works European Technology Platform expert working group on Future Networks and Management published a White Paper [85] which includes requirements and concepts related to this thesis.

> *'The final aim is to come with a flexible, scalable and robust end-to-end smart integrated network, which is able to cope with the requirements imposed by both fixed and wireless accesses infrastructures.'* [85]

Under the section 'Interworking' it is mentioned that Future Networks should consist of several heterogeneous networks, which share their virtualized resources. Also Future Networks are expected to support interfaces for enhanced manageability, 'for diverse services and for optimal access and utilisation of shared resources' [85].

Future Networks should support the design goals of software defined networks, which differentiate Future Networks from existing networks technologies: Functional Programmability and elasticity; Integrated Virtualization of Connectivity and In-Network Management.

The key features supported through Future Networks include three layers in hierarchical order. These are:

- Applications and services on top.
- Functional features for control, service-aware and management-aware functions together with virtualization functions in the middle.
- The underlying resources include networking, processing and storage at the bottom. Each layer is interconnected.

Efficiency. Network resources need to be used more intelligently and efficiently.

Resource Saving. Also the need to increase energy efficiency calls for an economical usage of network resources and for new techniques with learning capabilities on how to dynamically apply available resources in an optimal way.

The new network architecture should be capable of evolution and support for integrated services and Context-aware and Content-aware networking (Net!Works European Technology Platform, White Paper, Future Networks and Management [85])

3.2 Sources of Requirements in International ICT Projects

A list of ICT projects relevant for this thesis is presented and Cross Layer Optimization relevant requirements have been derived.

3.2.1 EU eHealth

One of the main Future Internet smart-city application domains and use-cases is eHealth. Ambient-Assist-Living (AAL) and virtualized health care shall efficiently improve remote patient diagnostic and rehabilitation as part of those research activities. Closed enterprise networks in hospitals shall be connected to remote mobile patient monitoring devices in the near future. A very high level of security in terms of reliability, performance and availability is demanded from such eHealth systems. Efficient transport of different data traffic classes and converged charging is required, too.

The integrated project 'Future Internet Social and Technological Alignment Research' (FISTAR) [25] will establish early trials in the health care domain building on Future Internet (FI) technology leveraging on the outcomes of FIWARE FI-PPP Phase 1. The main aim of FISTAR is to become self-sufficient after the end of the project in 2015 and to continue with a sustainable business model operated by several partners. In order to meet the requirements of a global eHealth industry, FISTAR will use a fundamental different 'reverse' cloud approach. Whereas the common cloud approach centralized data in unspecified locations, FISTAR aims to keep sensible patient data closed in the hospital and instantiates requires software functionalities within the hospital. The patient data will be processed in the hospital private data center cloud, without being transported to the public cloud. FISTAR is characterized by use cases, each of them individually describing a specific scenario, in which Future Internet technologies improve the State of the Art. Mobile telecommunication is a crucial part of this project to establish remote communication to patients, in which efficient connectivity management is required between the patient and hospital.

3.2.2 Real-Time Topology Optimization in SDN

Large scale telecommunication network deployment and its management require huge OPEX and CAPEX from the network operator. Network virtualization, Software Defined Network concepts and Cloud principles enable innovative approaches for introducing elasticity in the network to reduce OPEX. The activation and deactivation of network elements and their efficient interconnection is known as Network Design, which enables up- and downscaling of the parts of the entire network on demand based on the traffic situation. Adaptive Network Management through SDN controller functionalities introduces novel mechanisms to actively influence service data flows within the network with the goal to equally distribute the network load, increase reliability and reduce cost through deactivation of unused network parts.

The realization of such a scenario introduces new challenges to the system. The underlying Network Design problem needs to be solved according to requirements from the service level indicating the quality level on a per flow basis.

3.3 Requirements Identification and Analysis

This section summarizes high-level system requirements, which have been derived out of the before mentioned sources and white papers [143, 16]. The identified requirements have been aggregated, but not sorted with any order of their importance or priority. The following list of requirements has been separated into functional and non-functional requirements. Functional requirements define measurable aspects of the system whereas non-functional requirements address qualitative characteristic of the system.

3.3.1 Functional System Requirements

The following functional requirements have been derived from the different requirement sources presented above.

Authentication Users and service requests into the system from outside should be authenticated using existing security mechanisms. Each request originated from end user, service or user equipment should be verified before resources are granted.

Authorization Service requests should be authenticated before granting or revoking system resources.

Accounting and Charging Charging should be supported based on time and value: both combination or non charging should be supported.

End User Interaction An open control interface from the CLO function towards the end user or device is required. Dynamic and individual QoS requests and system statistics from the device towards CLO should be supported. The device should be able to retrieve service adjustment commands in return over this channel.

Network-aware Services The system should support an open control interface from the CLO function towards the network to signal resource demand into the network and retrieve statistics or event notification from the network in return.

Service-awareness towards Networks The system should support an open control interface from the CLO function towards the service to signal required service parameter (service data rates, codecs, etc.) to the CLO function and retrieve adjustments from the CLO function in return.

Self Adaptation The Cross Layer Optimization function should control the system through measurement and control interactions. Self-organization mechanisms and feedback loops should be supported for non-network-aware service support. The system state should be monitored and QoS policies should be applied dynamically.

Multi Layer Functions System optimizations should take the resources of different ISO/OSI layer into consideration while optimizing data traffic transport.

QoS Properties The system should support current Quality of Service mechanisms in today's networks and services.

Mobility Support Horizontal mobility is the ability of an entity to change its location while ensuring connectivity. Vertical mobility is the other dimension in which the position is not necessarily changed, but the network technology is toggled. Both forms of mobility should be supported by the system.

3.3.2 Non-Functional System Requirements

The following non-functional requirements have been derived from the different requirement sources presented above.

Integration Effort The system should be integrated into existing systems as a brownfield or evolutionary approach with minimal effect on devices, networks and applications.

Openness and Expandability The system should be extensible in the sense of continuous enhancements and extensions. Novel network technologies and innovative service types should be added at a later point to the system with minimal modifications.

Transparency The system should be transparent in standardized telecommunication networks and its usage should be optional to create value-added services and revenues.

Interoperability The system should work among different network operator domains, in which Service Level Agreements (SLAs) on traffic exchange exist.

Cost Efficiency The system should provide a solution for reducing cost (energy, OPEX and CAPEX) for the network operators and service providers.

Backwards Compatibility The system should support network-aware applications as well as today's non-network-aware applications.

Standard Conform The system should align with existing standardized interfaces for heterogeneous access- and core-network, service domain and device support.

Flexibility The system should be flexible in regard to heterogeneous access and core network technologies support.

Efficiency The system should approximately determine the best solution to optimizing data traffic transport.

System Dynamics Dynamic behavior for supporting real-time network adaptation with small delays should be supported.

Reliability The system should be reliable and available to the end user.

Scalability The system should be scalable in terms of network load and signaling overhead.

Elasticity The system should support elasticity of network components.

Usability The system should be intuitive for the end user to demand a certain level of QoS from the network. In addition, the network operators should easily control, manage and observe the system.

Requirements	3GPP EPC	3GPP IMS	IETF ALTO
End User Interaction	Not Supported	Limited supported	Not supported
Network-aware service support	Limited, with enabler	Not supported	Limited supported
Service-aware networking support	Limited, with enabler	Limited to SIP services	Not supported
Dynamic Traffic Engineering	Not supported	Not supported	Not supported
Adaptive Network Management	Not supported	Not supported	Not supported
Cost Efficiency/Optimization	Not supported	Not supported	Limited to peer selection
Heterogeneous Network Support	Supported	Supported	Supported
Context Information for PCC	Limited supported	Limited, with enabler	Limited supported
Openness and Expandability	Open	Open	Open
Device Capabilities	Very limited supported	Not supported	Not supported
Flexible Application Support	Supported	Limited to SIP based applications	Limitations to P2P and CDN
Scalability	3GPP scalability mechanisms	3GPP scalability mechanisms	Not supported
Usability	Transparent to the end user	Transparent to the end user	Implementation dependent
Availability	OpenEPC project	OpenIMSCore	No software available
Requirements Evaluation	Participially applicable	Limited applicable	Not applicable

Table 3.1: Comparison of Requirements against Related Work

3.4 Requirement Analysis, Discussion and Gap Analysis

All relevant requirements identified in the previous section have been analyzed in terms of applicability to Cross Layer Optimization concepts. This section selects specific requirements that are in the focus of this thesis and groups them. The order of the requirements has no relation to the requirements' importance and weight. Table 3.1 shows which of the main functional and non-functional system requirements are met by State of the Art solutions and concepts.

With regard to the identified requirements mentioned in Table 3.1 (see column

Requirements), three approaches with similar concepts have been identified during the State of the Art research. These are the 3GPP IP Multimedia Subsystem (IMS), the 3GPP Evolved Packet Core (EPC) and the IETF Application Layer Traffic Optimization (ALTO).

End User Interaction in form of user demanded QoS requests is not supported by EPC and ALTO. SIP based services might consider UE demanded parameters such as multimedia CODECs. No individual traffic or service class prioritization is supported.

Network-aware service support refers to the ability of services to directly interact with the network. The ALTO approach takes topology and network state information at the time of service selection into consideration. Neither QoS requests nor policies are enforced in the network, which allows for prioritization of Service Data Flows. SIP based IMS services are not network agnostic per se. The EPC concept exposes the Rx interface for querying policies from the network and retrieving status update notifications in return. Network technology related information is not provided per se, but can be exposed from the control plane to the application layer through additional enabler.

Service-aware networking support refers to the granular differentiation of Service Data Flows in the network. The IMS concept is limited to SIP based services to ensure dedicated resource guarantees in the network. Other (OTT) applications are not supported by IMS.

Dynamic Traffic Engineering and Adaptive Network Management are not supported through the compared related work.

Cost Efficiency/Optimization is only targeted by ALTO during the initial peer selection and service establishment.

Heterogeneous Network Support is supported by all compared solutions. ALTO is addressing P2P overlays and CDNs, which are operating on fixed as well as on mobile networks.

Context Information for PCC is supported by all solutions in part e.g. with connected network technology, time and location information. User preferences for a fine granular per flow, service or device level and device capabilities (screen resolution, battery state, available interfaces) are not supported by any solution mentioned under in Section 2.

Flexible Application Support discusses the application of the system to network and non-network-aware applications. IMS is limited to SIP based services, whereas EPC provides a larger range of IP applications and ALTO is limited to P2P and CDN.

The point Availability discusses the state of the presented approach. IMS and EPC concepts are available as software technical prototypes namely OpenIMSCore and OpenEPC. No free or Open Source ALTO software implementation was found during the time this thesis was written.

The ALTO approach allows networks to publish link and state information towards the ALTO Server/Service using the ALTO protocol. The ALTO server maintains a network map including costs and policies. ALTO clients, co-located at applications, are enabled to query the ALTO Server with service requests. The requests will be answered by the ALTO server based on proximity or other metrics in order to establish a better-than-random initial peer selection. Network topology and cost models are only abstractly taken into account without specific cost for network elements and links. ALTO aims to enhance network utilization in P2P systems through delivering the closest service given a geographical position of a peer. Network-awareness to services as well as service-awareness to networks is not available through the ALTO protocol. No mechanism for retrieving network state information has been presented in the ALTO protocol either.

The current 3GPP specified PCC architecture determines policy decisions solely based on static user profile information. Neither application requirements nor individual user demands have been taken into consideration yet. None of the available solutions presented in the chapter on related work allow Cross Layer application- and network-layer adjustments at the same time, in order to optimize the connectivity and ensure session continuity even in overload situations. Skype as a classic Over-The-Top (OTT) representative has a non-optimal ratio of information to bandwidth demand. In case of high packet-loss, the aggressive FEC concept very likely doubles packets with additional redundancy [130] and increases the total network load in overload situations even more.

The requirements, which have been selected for the evaluation are going beyond the standard and have been derived from the requirement sources listed in the beginning of this chapter.

3GPP has defined network elements for resource control and access network selection. The two 3GPP Rel. 12 standard components of the Evolved Packet Core for network management and policy control are Access Network Discovery and Selection Function (ANDSF) and Policy and Charging Rules Function (PCRF). Early concepts of adaptive access network selection, component scalability and heterogeneous network management are supported both through ANDSF and PCRF. No fine granular user demanded QoS requests can be realized with the presented solution of the related work. Neither user demanded QoS control nor dynamic network management or adaptive traffic engineering is supported.

3.5 Summary

This chapter presented and discussed the Requirements Analysis and Engineering on relevant and important requirements for NGNs and the Future Internet. Different sources of requirements were listed covering international organizations influencing the evolution of ICT, standardization bodies and recent international ICT project requirements. A Requirement Analysis, Discussion and Gap Analysis outlined the comparison of the individual approaches and validated those against the key requirements. None of the identified and presented solutions is capable of covering the requirements. There is no publicly available open solution of an ALTO implementation available, in contrast to OpenEPC and OpenIMSCore. The largest functional overlap between the requirements and the evaluated solutions has been identified in 3GPP EPC and IMS and the two corresponding projects OpenEPC and OpenIMSCore. Both will be further analyzed according to their applicability within the scope of the thesis.

The next chapter builds on the identified requirements and first specifies a generic architecture blueprint before the specification is presented as a whole.

CHAPTER 4

Cross Layer Optimization Concept and Specification

This chapter first presents a research discourse on the design aspects, followed by the Cross Layer Reference Architecture model design and finally specifies the fully Generic Adaptive Resource Control (GARC) functions.

The first part elaborates fundamental design aspects of the approach presented in this thesis. These design aspects are motivated through a gap analysis between state of the art and requirement analysis. The second main part builds upon the previous part and presents an abstract and generalized architecture. Finally, the third part presents the concept and specification of the Generic Adaptive Resource Control function together with its key reference points. [1]

4.1 Introduction

The previous chapter lists identified functional and non-functional requirements for QoS control and management. In this chapter, the requirements are further discussed and analyzed. A research discourse on the design aspects motivates design decisions of the conceptual model by the author and highlights n-key-functionalities of the presented architecture. Finally, the overall system specification is presented together with usage signaling patterns in form of sequence diagrams.

4.2 Research Discourse on the Design Aspects

This section compares the related work Section 2 with the previous Chapter 3 requirement analysis. A delta analysis points out the gaps between functionalities uncovered in the related work and necessary functionalities identified in the requirement analysis. In addition, this section elaborates fundamental design aspects of the approach, which build the basis for the following design and specification sections of this chapter.

The layered International Organization for Standardization (ISO)/Open Systems Interconnection (OSI) reference model (ISO/IEC 7498-1) divides communication systems, such as the Internet, into horizontal and independent layers. Each individual layer communicates only to both adjacent layers over well defined interfaces. According to the recommendation X.200, seven layers have been defined: 1) Physical, 2) Data Link, 3) Network, 4) Transport, 5) Session, 6) Presentation and 7) Application. The separation-of-concerns paradigm aggregates functionalities of the same type into the same functional block and assigns them to a specific layer. For this reason, today's IP applications assume pure best-effort IP connectivity, without implementing or influencing specific routing, session or mobility functionalities or adjusting access network specific parameters for the underlying connection.

On the one side the layered architecture eases the creation of new applications, the integration of new IP networks or the substitution of a whole layer theoretically, which is one of the success factors in today's Internet. On the other side the existing and well-established Internet Protocol creates a high burden for the introduction of new network layer protocols (e.g., IPv6, IPSec), which in turn addresses the weaknesses of Internet Protocol (v4,v6) as address shortage, mobility support,

[1] Results of this chapter have been published in [37, 38, 39, 40, 41, 144, 42, 145, 146, 147, 148]

insufficient security and flexibility, etc. Furthermore, additional transport protocols such as Stream Control Transmission Protocol (SCTP) [74, 149] or multipath TCP [150] require adaptations to be integrated into the network layer.

Functional Enhancement of ISO/OSI Layer through Cross Layer Optimization Cross Layer Optimization (CLO) is the concept of bridging the gap between application- and network-layer through creating awareness of each other by applying service-oriented concepts to networking for enabling direct control message exchange.

Figure 1.1 in the introduction 1 illustrates two different views on Cross Layer Optimization enhancements for the ISO/OSI Reference Model.

One model (M1) entitled Dynamic Simplified ISO/OSI Model in the upper right corner of the figure depicts the reduction of layers from seven independent down to three layers. The central layer is the Cross Layer Optimization or Mediation layer, which is in the focus of this thesis. This model also motivated by Foukalas et. al. in [10] and should point out the high and flexible interaction between the three remaining layers.

The other model (M2) entitled Cross Layer Optimization enhancements for the ISO/OSI Reference Model in the lower right part of the figure, positions the Cross Layer Optimization function as an external and layer independent network element. This model is also motivated by Carneiro et. al. in [11], Kellerer et. al. in [12], Raisinghani et. al. in [114] and interfaces the individual layers without merging or aggregating them.

Characteristics	**3 Layer (M1)**	**External Control (M2)**
Integration	Greenfield	Brownfield
Functional Control	Merged layer	Adapter concept
Interoperability	Difficult	Simplified
Acceptance	Limited	High
Signaling Traffic	Medium	Medium/high

Table 4.1: Different Cross Layer Optimization Functional Enhancement Strategies

These two different architecture models (M1 and M2) differ in the following aspects, which have been summarized in Table 4.1.

The 3 Layer model (M1) lacks any constraints and is regarded as a greenfield approach conceptually. Functions of the Physical, Data Link, Network and Transport layers are aggregated into a single network layer. In addition Session, Presentation and Application layer functions are similarly aggregated into one Application layer.

The external CLO control in model M2 remains the existing layer architecture in comparison to M1. M2 remains technology-independent by abstracting network technology details per layer through an adapter concept.

The difficulty in aggregating layers of M1 is solved through the flexible adapter concept of M2. Technology and layer specific specific programmable interfaces are abstracted over an adapter, which is in turn externally controlled by the CLO.

M1 requires clean slate environments, which are limited in terms of interoperability to existing network architectures. Therefore the acceptance of M2 is regarded as higher than M1.

The signaling traffic overhead for both models M1 and M2 are regarded as equal. Both models exchange equal layer specific data between the application and network layers.

The G-Lab DEEP project [22] aggregates the seven ISO/OSI layers conceptually into the three main layers a) network, b) Cross Layer Optimization and c) application. The introduction of an intermediate layer in between the application and network layer, enables dynamic feedback communication between the adjacent layers of CLO.

In conclusion and considering the arguments above, the CLO of this thesis will be designed as an external control element. Moreover the presentation of the simplified three layer architecture is kept for the conceptual part in order to indicate considered functions of the application and network layer more precisely.

Key Requirements for the Cross Layer Optimization Model The main benefit of introducing Cross Layer Optimization in existing networks (core networks or cloud data center) is the realization of the following key requirements

1. '*Network-awareness for applications*' Enable the individual adjustment and optimization of data traffic control based on service layer requirements.

2. '*Application-awareness for networks*' Enable the individual adjustment and optimization of active application-layer sessions based on network types or current traffic situations.

3. '*Overall system optimization*' Enable the inter and/or intra network domain resource optimization in terms of time, user group or set of service data flows (IP connections).

4. '*Costs savings*' Reduce Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) through enhanced Traffic Engineering or Network Management using CLO.

5. '*New Business Models*' Enable network QoS on demand or QoS-as-a-Service from the network operator towards the service provider or end user.

CLO needs to support bottom-up as well as top-down layered signaling to achieve the mentioned optimizations. Both synchronous and asynchronous signaling are required to ensure on demand and real-time adjustments. Thereby client or service side applications are enabled to signal application layer demands over (standardized) interfaces towards the underlying fixed and mobile access and core network and vice versa.

4.2.1 Cross Layer Optimization Reference Architecture

This section presents the theoretical specification and concept of the Cross Layer Optimization (CLO) Reference Architecture and its functional elements. Cross Layer Optimization aims to bridge the gap between the application- and network-layer through creating awareness of each other by enabling direct control message exchange.

The main characteristics of the Cross Layer Optimization concept are:

- Network-awareness for applications: Networks adjust data traffic control based on service layer requirements. A 3GPP Policy Charging and Control (PCC) architecture applies QoS on data streams and provides real-time network statistics, subscriber profiles and context information towards CLO. A network policy decision point may prioritize an emergency call in contrast to an entertainment multimedia connection.
- Application-aware networks: CLO enables applications to adjust active sessions based on network types or current traffic situations. A multimedia streaming application may reduce the resolution or quality in case of missing network resource availability.
- Dynamic, application specific and adaptive resource optimization: Static QoS rules from the application into the network layer have to be supported as well as dynamic adaptations in case of network changes (handover or utilization).
- Backwards compatibility to classic IP based applications: Today's applications without network resource reservation capabilities support need in-network functionalities such as Deep-Packet-Inspection (DPI) additionally to derive QoS requirements from real-time service invocation request.
- Direct and simplified interaction between the End User customer and the policy control system.

CLO supports bottom-up as well as top-down layered signaling. Thereby client or service side applications are enabled to signal application layer demands over standardized interfaces towards the underlying fixed and mobile access and core network and vice versa.

Figure 4.1 illustrates the three layers: application, Cross Layer Optimization and network, whose individual functionalities are presented in the following.

Application layer The *application layer* represents an abstraction of any IP or post-IP service such as a single service, complex IP Multimedia Subsystem and/or Service Delivery Platform. Network-aware applications support directly influencing the underlying network (if supported) or demanding network resources at the Cross Layer Optimization interface, which enforces network specific parameters. Network-aware applications may receive a notification event in case of network changes or guaranteed bit rate violation.

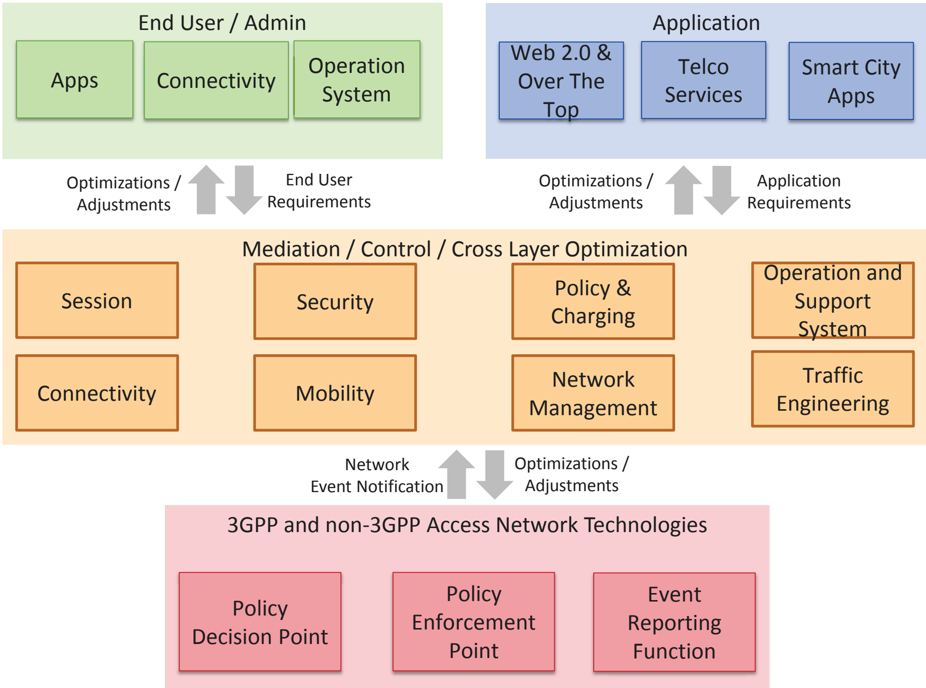

Figure 4.1: Cross Layer Optimization Reference Architecture and Message Flow

Cross Layer Optimization The main purpose of the *Cross Layer Optimization* is to optimize IP connectivity. Therefore generalized application layer network resource requests are transformed into specific access- or core-network resource requests. Incoming meta-data application requirements are transformed into network specific requests. A negotiation logic computes the optimized parameters which are enforced within the network. The optimization process may include loops or rounds in which a solution is computed, which fulfills the initial application requirements, is aligned with the available network capabilities and is authorized by the network operator and service provider.

The Cross Layer Optimization works transparently for today's applications that are not network-aware, but is also directly addressed by network-aware applications in order to perform network control and management tasks instantly. The correct mapping of requested and available resources is a challenge, in which meta requirement descriptions are transformed into specific network resource parameters, while keeping the same level of information.

Network layer The *network layer* encompasses 3GPP and non-3GPP fixed and mobile access and core networks. Next-Generation-Networks (IMS, EPC) as well as virtualized (OpenFlow) or functional composition future networks are integrated within GARC. Each network exposes a north-bound interface for exchanging control messages with the upper layers.

4.2.2 Cross Layer Optimization Life-Cycle Phases

Telecommunication systems are in a continuous evolution and affected by changing conditions and factors permanently. Such factors could be external factors (user mobility, radio signal reflection, interferences, etc.) or system internal factors (number of network component, network topology, system resources, etc.). Cell sizes e.g. vary because of external factors such as weather conditions, system load or component failures. Self-organization mechanisms and feedback loops should control the system through measurement and control interactions as depicted in Figure 4.2.

The life cycle should include phases for monitoring, analyzing, policy decision and policy enforcement.

The key states of the biology-inspired closed-loop are defined as:

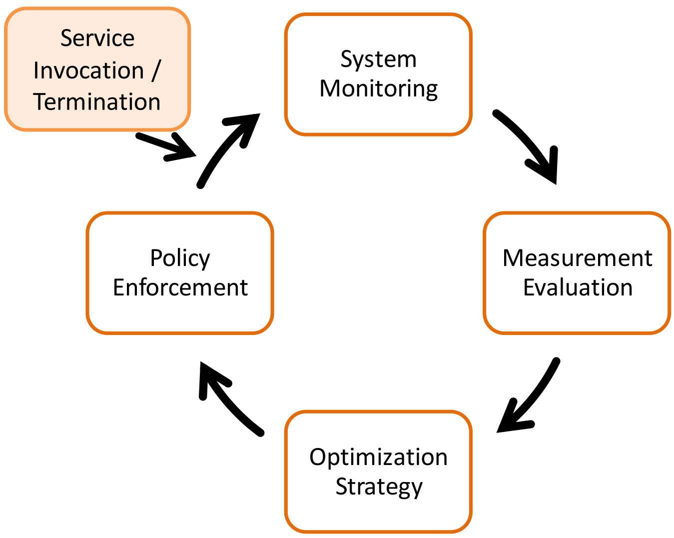

Figure 4.2: Cross Layer System Optimization Life-Cycle

1. System Monitoring: Real-time monitoring data is required to generate policy decisions based on the system state. Monitoring on distributed elements within the network such as UE, network elements and the actual service is required. Cross Layer monitoring information retrieved on different layers of each component opens up a new dimension of complexity, but aids in optimizing the overall system at the same time. Network parameters include jitter, packet-loss, throughput and application layer information energy consumption, system utilization.

2. Measurement Evaluation: Measurement data probes are collected, aggregated and evaluated centrally.

3. Optimization Strategy: Policy decisions are computed based on static profile and dynamic context and measurement information. These policies may affect

network and service layers in parallel. One or multiple parameters might be modified simultaneously. Network-aware services signal predefined values beforehand in order to adjust values in a predefined range. Continuous or discrete numbers are supported, whereas continuous numbers are changed in predefined steps between predefined upper and lower thresholds. Parameters of other - non-network-aware services - are changed in a best-effort manner. The optimization strategy takes heterogeneous access- and core-networks as well as services into the account of the optimization process.

4. Policy Enforcement: After determining the optimization strategy, the policy is enforced either in the network, at the service or both. Policy rules might be signaled to existing Policy Decision Points (PDP) (e.g. 3GPP PCRF or OpenFlow Controller) or to the service, which has no standardized PDP yet and therefore needs to adapt by itself.

The Cross Layer System Optimization life-cycle is influenced by external events such as initial service invocation or final service termination events. These service invocations may be reported directly to the Generic-Adaptive-Control-Function (GARC) or are identified over the data transport stream passively.

4.2.3 Openness and Expandability

Heterogeneous network and various service type support is required to increase the scope of the Cross Layer Optimization (CLO) function within a network. Therefore Openness and Expandability are key factors for the success of such a novel function.

The design should be kept modular in order to enable the substitution of individual functions.

The CLO function should support various heterogeneous network and service types over adapter concepts.

The CLO function should support different optimization strategies implemented as system logic.

New QoS supporting technologies should be supported fast and flexibly with minimal changes through the development of a new adapter.

Interoperability with existing telecommunication network components over standardized network protocols is required as much as possible.

4.2.4 Flexibility and Elasticity

Figure 4.3 summarizes the two potential strategic core network evolution paths.

The first option - characterized by over-provisioning - keeps the current architecture, but increases resources and capacities permanently. The second option - characterized by virtualization concepts - changes the architecture and modifies the core network in order to cope with the new requirements.

Both options have advantages and disadvantages as summarized as bullet points in the figure. The first option corrects selective geographical shortcomings in the

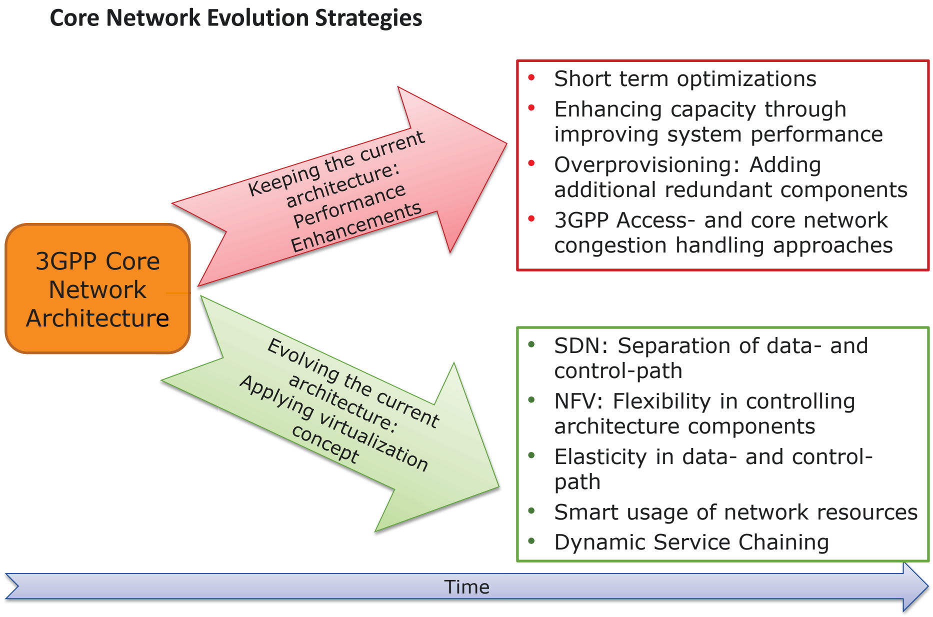

Figure 4.3: Core Network Evolution Strategies

network such as overload situations. The second option changes the concept and is therefore more adaptive to overload situations. In comparison to the first option, the second option is regarded as more scalable, efficient, flexible and robust for future demands on telecommunication networks. Virtualization in telecommunication networks is expected to utilize the resources more efficiently as stated by Urs Hoelzle (Google) in [44]. Therefore less active components are used to serve the overall demand, which becomes more advantageous in CAPEX and OPEX.

Figure 4.4 depicts the 3GPP core network technology evolution from 2G/GPRS over 3G/UMTS and HSPA towards 4G/EPS/SAE towards envisioned future successor architectures.

A trend of separating control from data plane can be recognized over time within the telecommunication network evolution. The network architecture is also becoming flatter, to increase the level of flexibility and elasticity.

4.2.5 System Scalability and Signaling Message Flows

System scalability is of high importance and the introduction of CLO (GARC) as a new single point of failure within the network needs to be avoided. The signaling messages flow needs to be optimized, as the following design aspect discourse in a Software Defined Networking / OpenFlow domain shows.

The amount of OpenFlow messages between OpenFlow Switch and OpenFlow Controller depends on the traffic characteristics mainly. This aspect comes from the

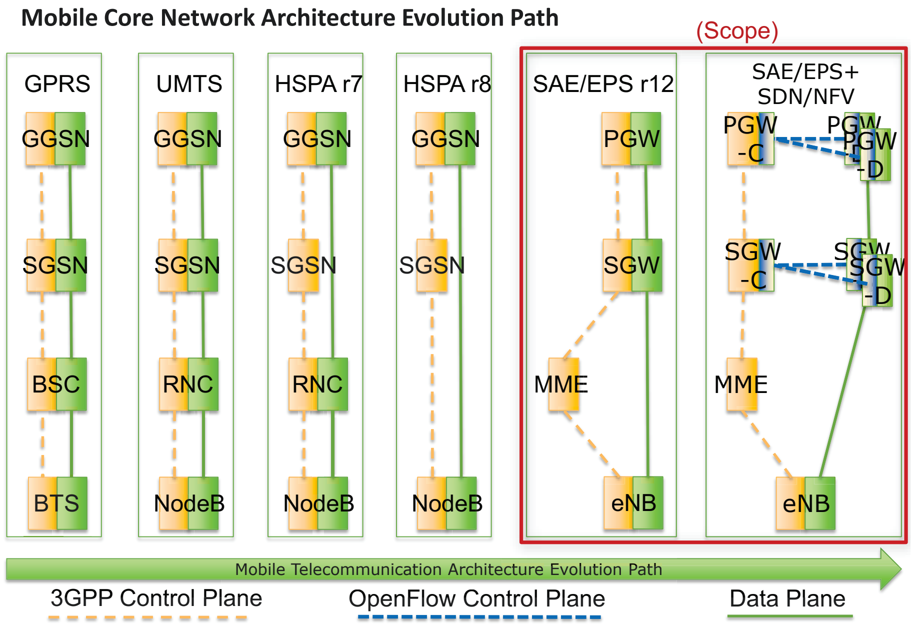

Figure 4.4: Telecommunication Core Network Technology Evolution

fact that known packet signatures (IP, port and protocol) from known IP service data flows are routed directly between OpenFlow switches without any additional controller invocation. In comparison, unknown packet signatures from new established service data flows, might condition PACKET-IN events at the OpenFlow Switch, which in turn trigger controller lookup messages. As an example, some flows of a long duration (video on demand streaming) might cause less OpenFlow lookup messages than one short flow invoking a website including many additional different embedded elements (advertisement, video, pictures, statistics, etc.).

The Cross Layer architecture envisages including scalability aspects in order to serve as much as queries while reducing the total amount of messages exchanged and improving the response time. The Cross Layer control functionality is required for interacting with the network layer directly. Three levels are identified namely (a) switch, (b) controller and (c) Cross Layer functional level. The three possible design decisions are presented in Figure 4.5.

The centralized approach (a) discusses the centralized approach in which only one Cross Layer Optimization function is orchestrating one or more networks over an adapter. Each flow routing request is transported out of the switch into the controller and further on towards Cross Layer function. Especially for SDN/OpenFlow networks, such a message flow slows down the time of reaction and therefore the connection establishment time is delayed. All the knowledge can be implemented within the CLO (GARC), which answers to incoming lookup messages. Each new flow requires the interaction of the OF Controller and CLO. Additional delay is in-

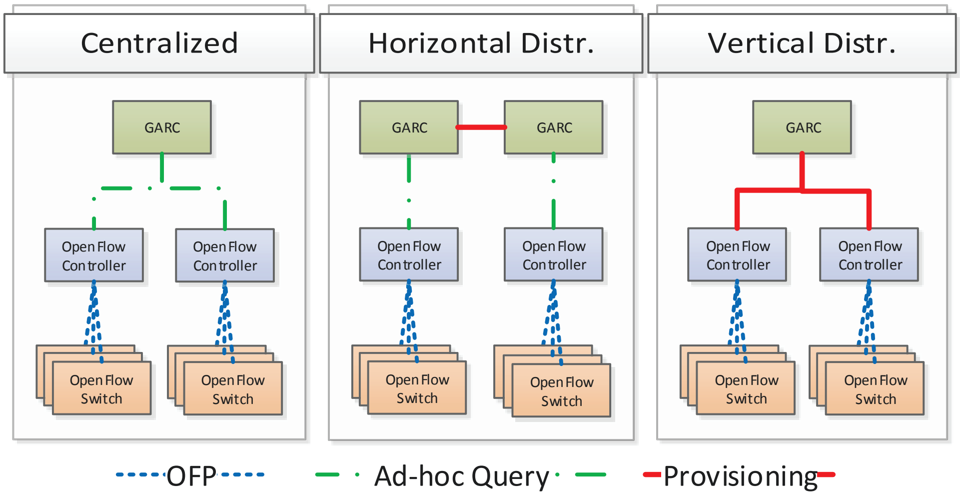

Figure 4.5: Architectural Comparison of Design Decisions

troduced, especially when CLO (GARC) and the OF Controller are geographically distributed.

Approach (b) depicts a distributed variant of GARC. One instance of GARC is responsible for the control of one tenant covering a set of OpenFlow Switches. Service data flows might traverse more than one OpenFlow network domain. Granted routing decisions and QoS guarantees for one OpenFlow network have to be communicated towards neighbored, adjacent OpenFlow network domains. Therefore synchronization between GARC instances over network boarders is required, for ensuring equal QoS treatment within all OpenFlow network domains along the data path.

Approach (c) presents the vertical distribution of control logic. GARC precomputes the network design and flow placement policies for the medium or long term based on current traffic pattern and the underlying network topology. Such flow placement policies are signaled from GARC towards the OpenFlow Controller once computed and generated per traffic pattern. A pre-provisioning of the policies from the controller in the switch decreases overall connection establishment delays too. Since the pre-computed flow placement policies have a longer validity, new flows do not require a lookup within GARC and routing decisions are performed in the OpenFlow Controller directly. OpenFlow Controllers have to be extended with extra functionalities, for supporting such routing logic over the northbound interface.

The taxonomy in Table 4.2 indicates the advantages and disadvantages of po-

Requirements	Centralized	Horizontal Distr.	Vertical Distr.
State Sync	no	yes	No
Vertical Hops	2	2	2
Horizontal Hops	0	1	0
Hops Total	2	3	2
Lookup	2	2	1
State Balanced	Short	Short	Long
Reliability	L+G	L+G	L
Redundancy	L+G	G	L
Efficiency	Poor	Medium	Good
Complexity	Limited	Higher	Higher
Evaluation	Limited	Medium	Good

Table 4.2: Comparison and Evaluation of Design Decisions

tential design approaches. Reliability and Redundancy are analyzed on a global (G) and local (L) scale in the taxonomy. Whereas approach (a) keeps the knowledge in GARC on a gloabl scale, variant (c) providions the SDN/OpenFlow Controller level below for reaching local redundancy. Local redundancy is regarded to be much more agile in regard to response times and signaling delays. Approach (c) is the preferred solution, since a maximal level of scalability and minimum connection setup delay can be achieved through this split of functionalities. Approach (a) is the simplest variant, which might be applicable for networks without a per flow routing schema.

4.2.6 Definition of Key Functionalities in the Design

A list of key functionalities for the Cross Layer Optimization functionality are mentioned in the following. The presented list is not prioritized and reflects the minimum set of required functionalities for demonstrating and validating a Cross Layer Optimization function prototype GARC.

- Generalized adapter concept for heterogeneous network support. The adapter should be designed generically in order to support current and future network technologies with QoS control functionalities.
- Generalized adapter concept for various network-aware application support. The adapter should be designed in a generic way to support current and future network-aware applications with QoS control functionalities.
- A flow placement logic module enhancing Traffic Engineering support. Routing decisions should be determined based on given service data flow requirements and available network resources.
- A network design logic module enhancing Network Management support. Controlling the life cycle of network elements such as routers, switches or gateways

is required in order to achieve resource savings.

- A module for Service Data Flow to QoS level mapping support. The module should be designed with expandability to support various metrics and algorithms.

- A modular Cross Layer Optimization functional framework for hosting the basic functionalities including reference points to external elements.

- Graphical User Interface (GUI) for virtualizing policy decisions and active network resource usage is required.

- Secure and independent network operator control. Network operators define policy sets for supported QoS rules within GARC. The rules of the network operator have a higher weight than external QoS requests on the policy decision process within GARC.

4.3 Cross Layer Optimization Input- and Output-Parameter

Current IP networks transport data traffic without taking application- or other external requirements into consideration. GARC is presented as an approach to solve this deficit. QoS demands from external stakeholders are derived from the user, device, network or context and are regarded as input parameters for the the process of determining the optimized policy decision by GARC.

This section summarizes and depicts the most relevant input parameters and observes that not all parameters are available in all networks at each point in time. Figure 4.6 depicts the input and output parameters used for GARC to be considered in the decision process, grouped by qualitative and quantitative parameters.

Many available input parameters need to be taken into consideration in order to determine the optimized solution. a weight factor is needed for each parameter to differentiate the individual importance of each parameter within the model. An optimization function computes an optimized policy decision based on all parameters. The policy decision generated by GARC is signaled to the network operator more as a recommendation than as a final decision. The policy decision is later to be enforced as an QoS Optimization Policy on individual network specific Policy Decision Points (PDP).

As a result, the QoE for the user should be improved by modifying one or many of the following parameters as shown for a multimedia connection:

Service Layer Modify current data-rate by changing video codec, video resolution, video frame rate.

Network Layer Change network priority after upgrading profile level or change access network.

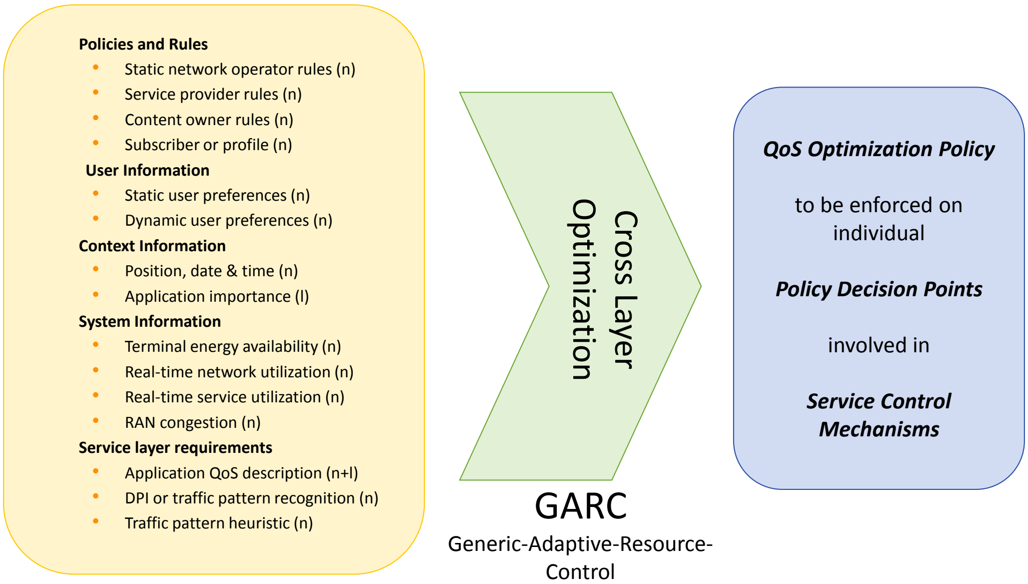

Figure 4.6: Qualitative(l) and Quantitative(n) Influences on Optimization Process

Table 4.3 summarizes the full set of potential input parameters presented as influences on the policy decision process of GARC. The table distinguishes between qualitative (relative value) and quantitative (numerical value) parameters. The parameters are aggregated in groups of policy and rules as well as context, user and system information plus service layer requirements.

4.4 High Level Cross Layer Optimization Function Architecture Model

This section outlines the main functional blocks of the Cross Layer Optimization function, namely Generic-Adaptive-Resource-Control (GARC). GARC is depicted in Figure 4.7 together with three novel reference points.

4.4.1 Architecture Functional Blocks

The high level Cross Layer Optimization functional architecture of GARC is split into three groups of 1) Control reference points, 2) Control Logic and 3) Network reference points as depicted in Figure 4.7.

Qualitative(l) and Quantitative(n) Influences		
Policies and Rules	Static network operator rules	n
	Service provider rules	n
	Subscriber or profile	n
	Content owner rules	n
Context Information	Device position and location	n
	Application importance	l
User Information	Static user preferences	n
	User subscription tariff	n
	Dynamic user preferences	n
System Information	Terminal energy availability	n
	Terminal screen resolution	n
	Real-time network utilization	n
	Network transport costs for the user	n
	Network transport costs for the provider	n
	RAN congestion situation in the network	n
	RAN congestion situation on the path	n
	3GPP ANDSF suggestions	n
	Real-time service utilization	n
Service layer requirements	Application QoS description	n+l
	DPI or traffic pattern recognition	n
	Traffic pattern heuristic	n

Table 4.3: Qualitative and Quantitative Influences on the Policy Decision Process

The main functional building blocks enabling the control reference points are:

- Application Interface - from GARC towards the network-aware applications.
- GARC Monitoring Interface - from GARC towards the eternal graphical user interface.
- 3GPP Diameter Interface - from GARC towards 3GPP telco service domains (IMS/EPC).
- End User Interface - from GARC towards the end user device.

The main functional building blocks of the control logic are:

- Cross Layer Resource Control and Optimization - The control and optimization logic within GARC. Various input parameters (network measurements, user preferences, network operator policies, context, costs and weights) are the basis for a policy decision process within this functional block. An optimization function computes the optimum based on metric (min costs, energy level, etc.). As a solution, a decision on a specific action is enforced in the operator network using operator policy control elements (e.g. PCRF). Modification of QoS level, adaption of routing through active flow placement, vertical

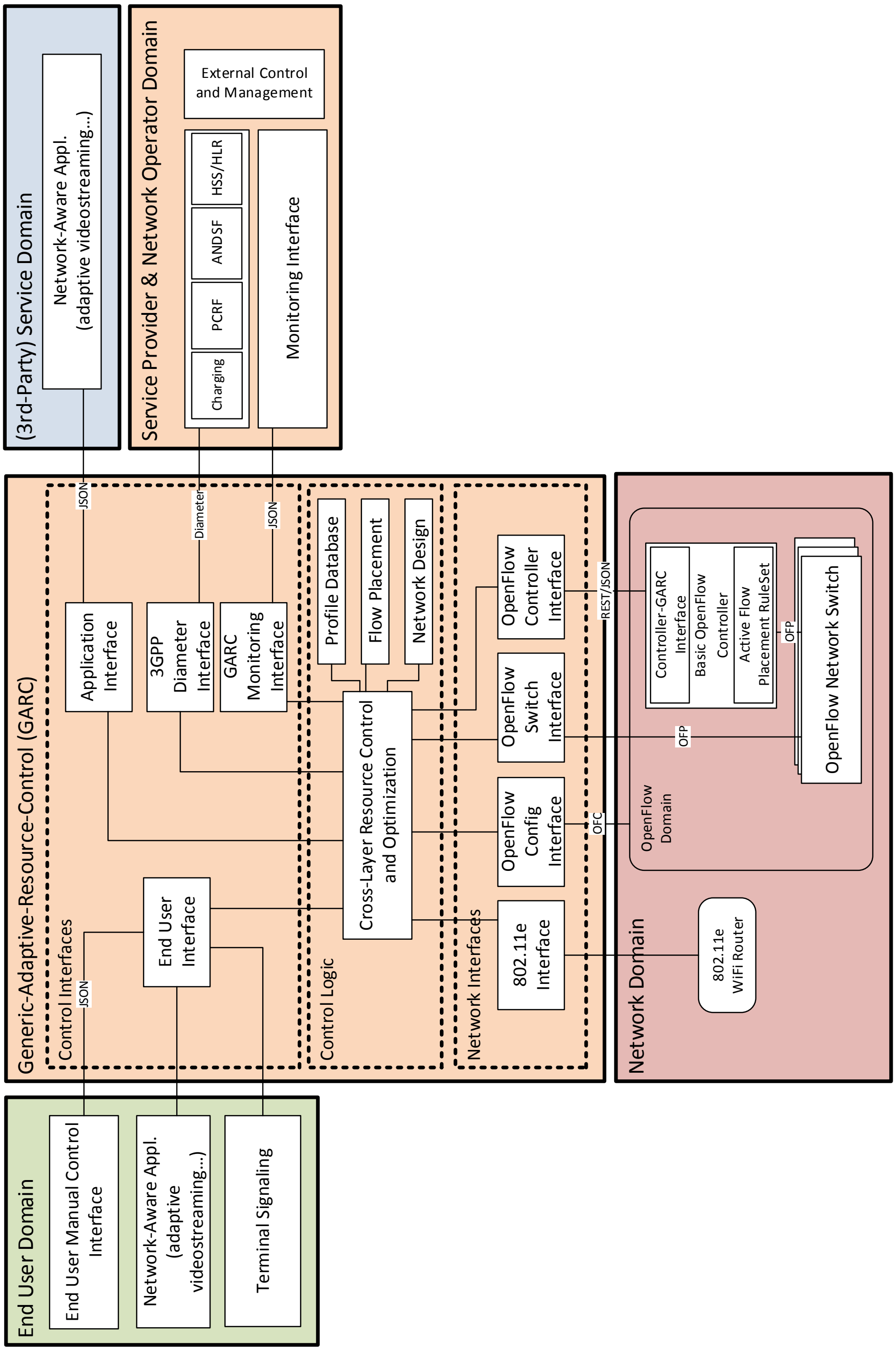

Figure 4.7: GARC Full Functional Architecture and Reference Points

handover or adaptive network design (for a log term view long term) are potential optimization options. The output of the decision process follows the formulation of the policy decision for the network operator PCC architecture.

- Profile Database - The database in which the state of the flow is kept.
- Flow Placement - A functional module for assigning priorities to individual flows, which might include re-routing in the network as well.
- Network Design - A functional module for dimensioning the network through enable/disable network elements based on the result of an objective function (minimize energy consumption, ensure the level X redundancy, over-provisioning of the network capacity with the factor of Y%, etc.).

4.4.2 Reference Points

The main functional building blocks enabling the control reference points are:

- Application Interface - from GARC towards the network-aware applications.
- GARC Monitoring Interface - from GARC towards the external graphical user interface.
- 3GPP Diameter Interface - from GARC towards 3GPP telco service domains (IMS/EPC).
- End User Interface - from GARC towards the end user device.

The main functional building blocks of the network interface layer are:

- IEEE 802.11e - An interface for marking frames on layer 2 with code points.
- OpenFlow Config Interface - Management and control of the OpenFlow domain including physical and virtual switches and controller.
- OpenFlow Switch Interface - Direct communication to the OpenFlow switch without involving the controller.
- Northbound/OpenFlow Controller Interface - One example for the yet unspecified SDN Northbound API between SDN controller and SDN application.

In addition, several system-internal interfaces between the functional blocks have been envisioned, but not specified further. These are beyond the scope of this high level functional reflection.

4.5 Core Cross Layer Optimization Functional Element Specification

The GARC Control Logic aggregates the Cross Layer Resource Control and Optimization Module, Optimization and Negotiation Module and the Active Flow Placement Module. The modular design enables the substitution of different functional blocks for special purpose network topologies or scenarios.

4.5.1 Cross Layer Resource Control and Optimization Module

The GARC Cross Layer Resource Control and Optimization Module is the centralized controller performing policy decisions in GARC plus handling and controlling signaling messages between different modules in GARC.

The state of each connection is kept within this module while dispatching input and output signaling messages.

Relevant packet-loss thresholds extracted from the network and QoS level on a per flow and end-user basis are stored in a stateful manner. All external input parameters are transformed and signaled further to GARC using one of the three main interfaces.

Finally a reasoner assigns weights to each parameter of a policy and determines an optimal solution. The reasoner can be enriched with meta data on the user, context, network condition, etc. as described under influences 4.6. Topology information of the transport network and application layer load statistics can be applied, too, in case the size of the network is limited in size (business network) and the scalability of the system is not challenged. Topology includes a representation in the form of nodes and links. Nodes have attributes (ID, type of hardware/software, required permanent). Links have dynamic and static parameters such as maximum capacity, current load, number of active flows. Such a solution is further signaled as a network policy over one or more of the three main GARC interfaces towards the network, service or device endpoint.

Session continuity directly influences the Quality-of-Experience (QoE), which needs to be ensured even in network overload situations. Therefore a smart optimization logic is required, which evaluates potential parameters of optimizing connectivity by adjusting application or network layer parameters. This might be the CODEC adjustment of a multimedia streaming server, the selection of a higher prioritization level over a period of high network utilization or the re-positioning of a virtual network function. QoS levels are mapped between the following QoS formats and value spaces depending on the underlying network technology:

- IEEE 802.11e-2005 Enhanced Distributed Channel Access (EDCA)
- IEEE 802.3 Ethernet
- Differentiated Services Field Codepoints (DSCP)
- 3GPP Quality of Service Class Identifier (QCI)
- OpenFlow protocol specific QoS parameters (queues/slices)

The GARC internal bearer table maintains a data structure of all monitored traffic flows that have a certain amount of QoS higher then the best-effort class. Each bearer is identified using source and destination IP and port together with the protocol as Traffic Flow Template (TFT).

The Optimization and Negotiation Module allows the realization of value added services on mobile networks. The definition of individual QoS policy rules over regular expressions by the end user, customer, or service provider enables new revenue streams for the network operator for selling QoS as a Service towards the end user customer.

These are supported QoS profile examples of GARC:

- QoS level X for any IP Service Data Flow between application Y running on a specific server towards the device. Examples are: Multimedia streaming services of YouTube.com [151, 152],
- All IP Service Data Flows from and to a company network realm X and/or IP address Y.
- All flows between 9:00 AM and 17:00 PM.
- All IP Service Data Flows having real-time characterizations.
- Choose the optimal network for a specific service or class of service. A policy evaluation might cause a vertical handover between heterogeneous access networks into an adjacent network with more suitable network conditions for the service.

4.5.2 Mathematical Preliminaries and Definitions

This section first presents mathematical preliminaries and definitions for understanding the approach followed within this thesis. First a short motivation for the approach presented later is given in the following.

The GreenTouch Green Meter Research Study entitled 'Reducing the Net Energy Consumption in Communications Networks by up to 90% by 2020' [153] investigates the energy consumption of technologies, architectures, components, devices, algorithms and protocols in ICT.

The main hypothesis is that the predicted traffic growth in future networks can be supported while at the same time reducing the total energy consumption of the networks significantly.

The term energy efficiency has been defined as the ratio of data traffic being carried by the network to the total energy required to support that traffic over the duration of one year.

The research on energy efficiency is motivated by the overall traffic growth in the Internet. The global Internet traffic grew more than 100-fold in the decade of 2000-2010 and over the decade 2010-2020 global wireline Internet traffic is expected to grow to approximately 16 times its size according to [153]. The global mobile Internet traffic alone will multiply by a factor of approximately 150 between 2010 and 2020.

It is important to notice that the network power consumption in 2010 is dominated by the power consumption of the routers and transponders and is a constant

Energy-saving Approach	**Gain Factor**	**Subsystems affected**
Power shedding	2.6x	Ethernet LAN
Sleep mode	2x	Ethernet LAN
Energy-efficient hardware (HW) design	1.2x	All hardware

Table 4.4: Energy-saving Approaches and Gain Factors for Related Subsystems

independent of the traffic. A demand oriented optimization of the energy consumption aligned to the traffic situation is expected to be recognized in 2020.

A not further specified family of Mixed Integer Linear Programming (MILP) models has been built to measure those values. The MIPL algorithm computed physical topology optimization. Power shedding of network elements has a large influence on network elements and routers specifically according to Table 4.4 from [153].

It is expected that the available hardware will continue becoming more efficient according to Moore's law for CMOS, which will also influence the overall efficiency and energy consumption positively.

The following two sections on elastic Network Design 4.5.3 and adaptive Flow Placement 4.5.5 require Mixed Integer Programming (MIP) and graph theory. Therefore this subsection summarizes the mathematical preliminaries and definitions.

The ideas and concepts of GARC, Network Design and Flow Placement presented in the next subsections have been published successfully under IEEE ICCCN [42] and SDN4FNS 2013 [145] was also part of the Master Thesis 'Design and Implementation of an On-Demand Network Management Module for Telecommunication Networks 'at TU Berlin [146] in cooperation with the Fraunhofer Institute FOKUS.

The physical infrastructure of large scale telecommunication networks usually abstracts to a logical network used for routing. Each node consists of many line cards that are grouped together to form a logical node for routing. This comes from the fact that even the newest hardware does not provide sufficient capacity to support our largest nodes. Further it is much cheaper to extend a network node by adding new line cards instead of replacing the old hardware entirely. Since the logical nodes consist of several line cards, the logical links also collapse to a set of physical lines.

If not otherwise specified, we use the notation of Korte & Vygen [154]. However the following notations are presented for the sake of consistency. Throughout these sections, we denote the logical network by $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ and its physical representation by $G = (V, E)$. The terms physical representation and physical network are used interchangeably. The physical network contains one vertex for each line card in the network and an edge connecting two nodes if and only if there is at least one physical line connecting the two line cards.

Since line cards usually have several ports, it is often the case that several physical lines connect two line cards as depicted in Figure 4.8. However in our mathematical graph representation, we contract such edges, hence the graph G is simple.

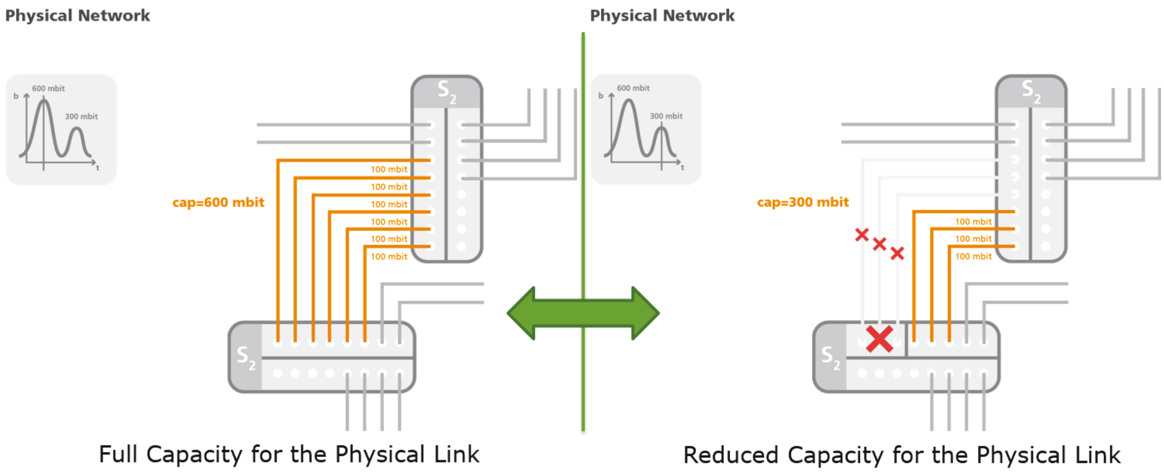

Figure 4.8: Demand Oriented Line-Card and Port Trigger

The logical network contains one vertex for each logical node and an edge $\{u, v\}$ connecting two nodes if and only if there is at least one physical line connecting a line card of u with a line card of v. The physical representation, i.e. the line cards, resp. physical lines, of a logical vertex $\bar{v} \in \mathcal{V}$, resp. logical edge $\bar{e} \in \mathcal{E}$ is denoted by the sets $V_{\bar{v}} \subseteq V$, resp $E_{\bar{e}} \subseteq E$.

Note that $V = \dot{\bigcup}_{\bar{v} \in \mathcal{V}} V_{\bar{v}}$ and $E = \dot{\bigcup}_{\bar{e} \in \mathcal{E}} E_{\bar{e}}$ holds, i.e. the entire logical network decomposes into sets of disjointed physical objects. For the sake of readability we sometimes also exploit the notation $V_{\bar{e}}$ to denote the set of physical line cards incident to a logical link $\bar{e}$. Consequently, the logical network arises from the physical network by a contraction of the sets $V_{\bar{v}}$. Usually, all line cards in a logical node are connected to each other via some internal structure. Hence we could assume that each of the sets $V_{\bar{v}}$ forms a clique of size $|V_{\bar{v}}|$.

However for practical reasons we do not include these edges in G, thus the sets form a stable set in G. Each physical line card $v \in V$ has a cost $cost : V \to \mathbb{R}_{\geq 0}$ assigned, that occurs if it is activated. The bandwidth capacity of a physical line $e \in E$ is denoted by $cap : E \to \mathbb{R}_{\geq 0}$. The capacity contributes to the total logical bandwidth if and only if edge e is active. An edge is active if and only if both of its endpoints are active. Finally, we introduce a traffic demand $d : \mathcal{T} \times \mathcal{C} \to \mathbb{R}_{\geq 0}$ for each traffic pattern and commodity.

We present a generic optimization scheme in which any, under mild assumptions, routing formulation $\mathcal{R}$, that is formulated as a mixed integer program (MIP), can be plugged in. **The objective of the optimization scheme is to minimize the weighted operational cost arising in each of the traffic patterns that need to be supported.** This objective is illustrated in the next two figures. An abstract network topology representation with meta data is depicted in Figure 4.9 An routing pattern has been applied to the network architecture in Figure 4.10.

The abstract network topology representation enhanced with the meta data of

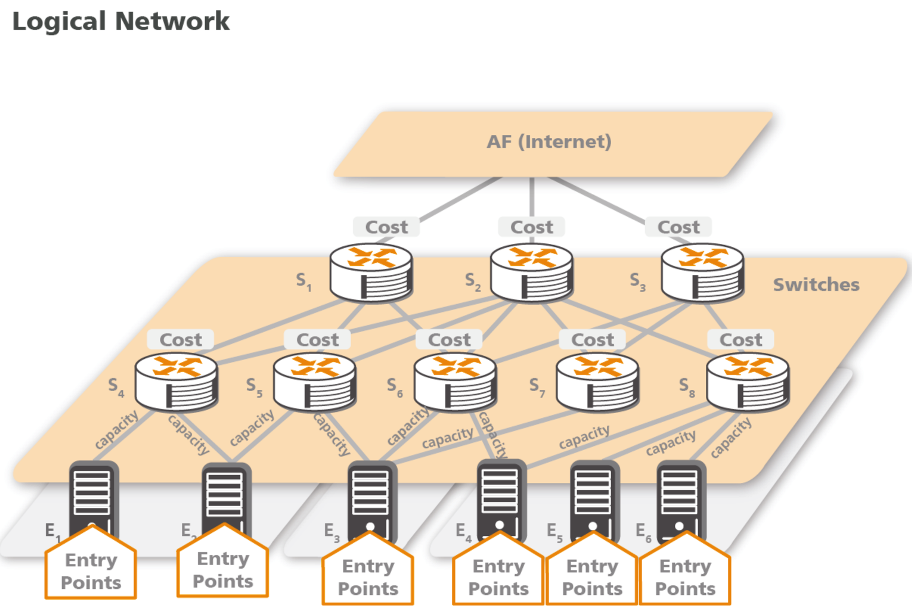

Figure 4.9: Network Topology Representation Enhanced with Meta Data

network element is regarded as input for the algorithm. The calculation takes meta data information such as costs, availability constraints of network elements and cost per network element into consideration. With the help of these meta description, constraints for ensuring the availability of at least one PGW in the data plane of an EPS can be met.

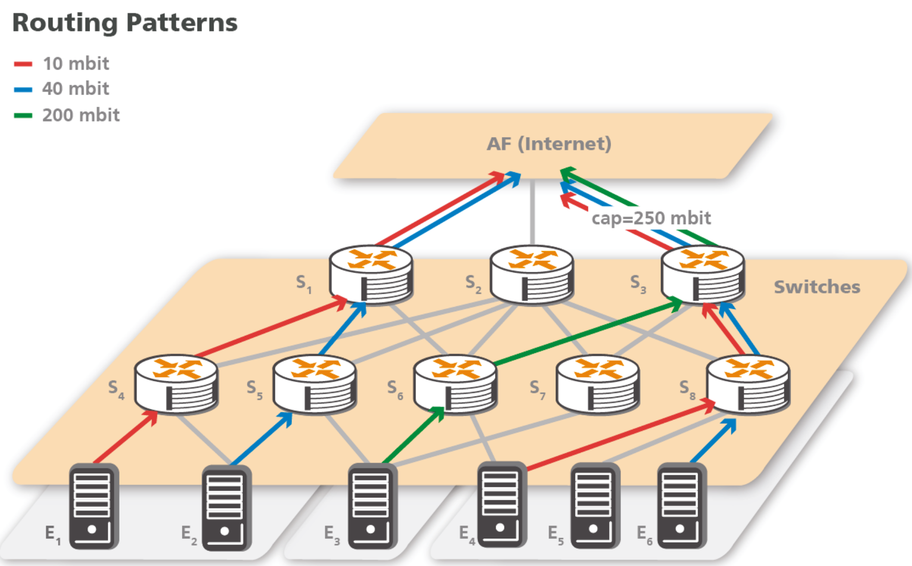

Figure 4.10: Network Topology Representation With Applied Routing Pattern

We assume that $\mathcal{R}$ induces capacity requirements $b : \mathcal{E} \times \mathcal{T} \to \mathbb{R}_{\geq 0}$ for each logical link $\bar{e} \in \mathcal{E}$ and traffic pattern T. Instead of formulating the operational cost arising from the physical network in a straight forward way, i.e. by introducing variables for each physical link and physical node, we use a Dantzig-Wolfe decomposition of blocks of these variables. For this, we state some observations in Section 4.5.3. Following in Section 4.5.4, we present the generic optimization scheme.

4.5.3 Elastic Network Design Module

The Elastic Network Design Module is one of two key functional elements, which seeks to apply existing concepts of the mathematical discipline of graph theory to networks.

A novel concept for elastic Network Design is presented, which interacts with the network as well as the applications. The Generic Adaptive Resource Control (GARC) is positioned in between the network and application layer and mediates Cross Layer QoS among them. The GARC function is positioned as an optional element in the operator core network for enabling those novel features. In particular and in the discussed use case, GARC retrieves real time data path information from OpenFlow switches and is therefore able to identify overload situations in the network precisely.

An example is provided for the Evolved Packet System in Figure 4.11. Whereas all network elements are enabled during peak times of a traffic pattern, selected network elements are disabled during off-peak times. The question of which network element to trigger in times of availability is calculated through the presented algorithm for minimizing the weighted operational cost.

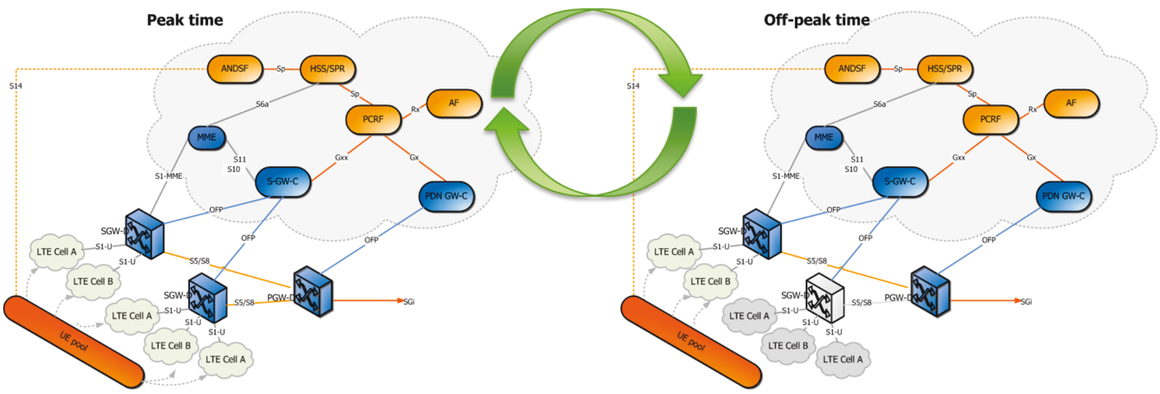

Figure 4.11: Elastic Network Design Module Example for Evolved Packet System

The network topology is modeled as a graph within GARC and the data structure is aligned on the mathematical preliminaries of the previous paragraph. GARC controls and manages network topologies and controls network resources dynamically and on demand. **The mathematical model of the network topology assists in optimizing the data plane topology and activates or deactivates entire network elements, line cards or individual ports for cost savings.**

Unused parts of the network can be deactivated during the night for cost savings, other parts in the network can be extended flexibly during peak hours. The Elastic Network Design Module controls a complex life cycle, which is elaborated in 4.7.2 in more detail.

Consider a fixed set of routing paths and therefore capacity allocations that need to be supported in a single traffic pattern T. Then the minimal operational cost required for this specific scenario can be evaluated by solving the problem (MCPEP1) below. We denote the problem of determining the minimal operational cost for a scenario with *The Minimal Cost Path Embedding Problem (MCPEP)* which is NP-hard according to Theorem 1.

The reader can use a simple reduction from a special case of the partially ordered knapsack problem for the proof of the theorem.

Theorem 1 *MCPEP is NP-hard.*

(MCPEP1)

$$\min \sum_{v \in V} cost(v) \cdot x_v \quad s.t. \tag{4.1}$$

$$\sum_{e \in E_{\bar{e}}} x_e \cdot cap(e) \geq b_{\bar{e}} \qquad \forall \bar{e} \in \mathcal{E} \tag{4.2}$$

$$x_v \geq x_e \qquad \forall v \in V, \forall e \in \delta(v) \tag{4.3}$$

$$x_v \in \{0,1\} \qquad \forall v \in V \tag{4.4}$$

$$x_e \in \{0,1\} \qquad \forall e \in E \tag{4.5}$$

The problem formulation contains binary variables x_v and x_e for each physical line card and physical line. A variable is set to one if and only if the corresponding physical object is active. Constraint (4.3) makes sure that a physical line is active if and only if both end points are active. Constraint (4.2) ensures that sufficient bandwidth is allocated on each logical link. Finally, the objective function minimizes the total operational cost arising from active objects. Due to the nature of the instances arising in our context, (MCPEP1) is usually highly block angular. Hence we can decompose the problem into several subproblems, which can be solved independently. The block structure comes from the following simple observation that is formalized in Definition 1. If the physical hardware of a single logical link is independent of the physical hardware of all other logical links, then the variables in the optimization problem (MCPEP1) can be set independently of all other variables. This observation can also be generalized to bigger subgraphs for which the physical hardware remains independent. With help of Theorem 2, we can even find all diagonal blocks in linear time using a breath first search and the definition of independent subgraphs.

Definition 1 *A subgraph $\mathcal{G}' = (\mathcal{V}', \mathcal{E}') \subseteq \mathcal{G}$ is called* ***independent*** *if and only if*

1. $\forall \bar{e} \in \mathcal{E}', \forall \bar{f} \in \mathcal{E} \setminus \mathcal{E}' : \forall e \in E_{\bar{e}}, \forall f \in E_{\bar{f}} : e \cap f = \emptyset$,

2. *there is no subgraph $\mathcal{G}'' \subset \mathcal{G}'$ with the above property.*

Theorem 2 *For any instance $\mathcal{I}$ of MCPEP, there exists a unique decomposition into independent subgraphs $\mathcal{D}$. Further, any solution x^* of $\mathcal{I}$ can be expressed in terms of solution to the subproblems in $\mathcal{D}$, i.e. for all $x^* \in sol(\mathcal{I})$ there exist solutions $x_D \in sol(D)$ for each $D \in \mathcal{D}$, such that $x^* = \sum_{D \in \mathcal{D}} x_D$.*

Now for each independent subgraph, we can generate a lookup-table which contains an optimal solution for each possible bandwidth requirement value. We denote the problem of determining a lookup-table for an instance of MC-PEP1 with *The Partially Ordered Knapsack Lookup Table Generation Problem (POKP-LTG)*. Due to space restrictions, we give an idea for the generation of such a table for independent subgraphs which contain exactly one logical link $\bar{e}$. For such subgraphs, we can easily see that any assignment of bandwidth requirements in the interval $[0, \sum_{e \in E_{\bar{e}}} cap(e)]$ results in a feasible solution for the corresponding formulation. Suppose that we found an optimal solution for a specific bandwidth requirement value $b^T_{\bar{e}}$. Then Theorem 3 states that the solution remains optimal within a certain interval. Our proof uses a simple exchange argument. Similar results can be stated for bigger independent subgraphs. Note that even if the lookup-table has polynomial size, generating such a table might still take an exponential amount of time. However, after the table has been created, we can lookup an optimal solution to any bandwidth value b in $O(logn)$, where n denotes the total number of variables in (MCPEP1).

Theorem 3 *Let $\mathcal{I}_b$ be an instance of Min-POKP with item set $\mathcal{N} = [n]$, weights $w : \mathcal{N} \to \mathbb{R}_{\geq 0}$, cost $c : \mathcal{N} \to \mathbb{R}_{\geq 0}$, precedence constraints $P = (N, A)$ and bandwidth requirement b. If x^* is an optimal solution of $\mathcal{I}_b$ with cost c^*, then x^* is optimal for all instances $\mathcal{I}_{b'}$ with $b' \in [b_\ell, b_u]$, where $b_u := \sum_{i=1}^n w_i x_i^*$ and $b_\ell := \min\{b, \max\{\sum w_i x_i : \sum x_i c_i \leq c^* - 1, x_i \in \{0,1\}, x \text{ closed under } P\} + 1\}$.*

With help of the theorem, we can easily construct a lookup-table by iteratively solving the problem for rising values of b, the bandwidth requirement. After a solution x^* has been found, the solution is optimal for the entire interval $[b_\ell, b_u]$. Hence the next bandwidth value to be evaluated is $b_u + 1$. Even though there are instances for which the lookup-table has exponential size, this is not the case in our scenario. Theorem 5 states that the number of intervals in a lookup-table is polynomially bounded, if the capacity and cost values are drawn from a finite set.

Theorem 4 *There are instances of POKP-LTG for which any partition has exponential size.*

Theorem 5 *Let $\mathcal{I}$ be an instance of POKP-LTG with weight and cost drawn from a finite set, i.e. $w_i \in \{u_1, ..., u_\ell\}$, $c_i \in \{c_1, ..., c_m\}$ and let ℓ_i, resp. m_i denote the number of elements with weight w_i, resp. cost c_i. then the optimal partition of $[0, \sum w_i]$ has at most $\min\{(\frac{n}{\ell} + 1)^\ell, (\frac{n}{m} + 1)^m\}$ intervals.*

4.5.4 Routing Formulation

With help of the lookup-tables from the previous section, we can express the operational cost arising from a fixed independent subgraph and traffic pattern through a convex combination of the solutions in the lookup-table. Instead of introducing variables for each physical line card and physical line, we introduce pattern variables π.

Definition 2 *A pattern $\pi \subseteq V \cup E$ for $\mathcal{I}_b$ is a set of physical line cards and physical lines such that Q is closed under the partial order of $\mathcal{I}_b$.*

Definition 3 *Let π be a pattern for $\mathcal{I}_b$, then we denote the cost, resp. capacity of π by $cost(\pi) := \sum_{v \in Q} cost(v)$ and $cap(\pi) := \sum_{e \in Q} cap(e)$*

Definition 4 *If a complete set of pattern variables is given, the set $\Pi(D), D \in \mathcal{D}$, resp. $\Pi(\bar{e}), \bar{e} \in \mathcal{E}$ denotes the set of all pattern variables that contain an independent subgraph D, resp. contain a logical link $\bar{e}$.*

Consequently, each of the blocks can be formulated by an inner representation consisting of extreme points $\pi_i \in \Pi(D), i = 1, ..., |\Pi(D)|$.

(MCPEP-PAT)

$$\min \sum_{i \in \Pi} cost(\pi_i) \quad s.t. \tag{4.6}$$

$$\sum_{\substack{i \in \Pi: \\ \bar{e} \in \pi}} cap(\pi_i) \geq b_{\bar{e}} \quad \forall \bar{e} \in \mathcal{E} \tag{4.7}$$

$$\sum_{i \in \Pi} \pi_i \leq 1 \tag{4.8}$$

$$\pi_i \in \{0, 1\} \quad \forall i \in \Pi \tag{4.9}$$

With the formulation of (MCPEP-PAT), the generic optimization scheme can now be formulated. It consists of the routing formulation $\mathcal{R}$ and a block of type (MCPEP-PAT) for each independent subgraph D and traffic pattern T. The objective function minimizes the total weighted operational cost arising from all traffic patterns and independent subgraphs. The formulation basically corresponds to a Dantzig-Wolfe decomposition of a straight-forward formulation, where each network design block of type (MCPEP1) is replaced by an inner representation using the formulation (MCPEP-PAT).

4.5.5 Adaptive Flow Placement Module

Three important and novel aspects are included in this module which are (1) fine granular per flow prioritization, (2) dynamical real-time network (re-)design enabling elasticity in the network and (3) active service-data-flow-placement or re-routing through graph theoretical methods. Recent statistics and forecasts until 2016 [18] from CISCO indicated video with more than 70 percent as the dominant factor in the overall mobile data-traffic breakdown. The total duration of connections is hard to guess from the network perspective.

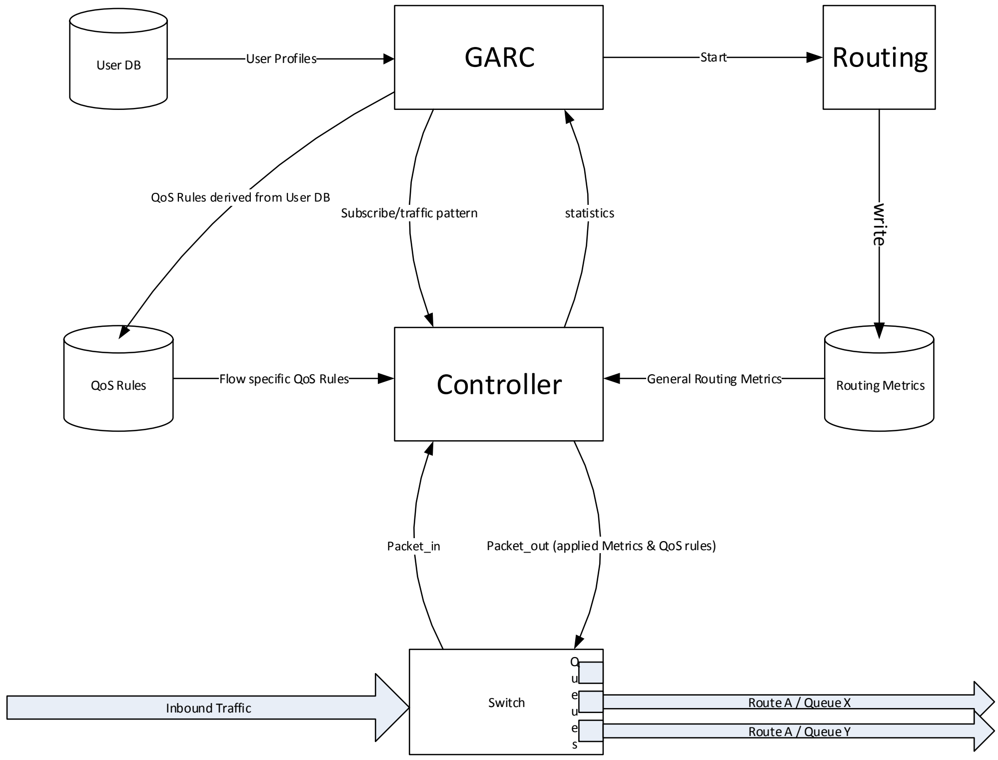

Figure 4.12: Proactive Flow Placement Functional Architecture and Reference Points

Figure 4.12 depicts the proactive Flow Placement functional architecture and its reference points. A reactive trigger point mechanism has been specified, which operates on initially installed thresholds. Those thresholds are evaluated based on real time network events (such as packet loss ratio, new service data flow, etc.). After successfully evaluating a trigger point, the upper layer control functions are notified. In case of the SDN/OpenFlow network architecture depicted in 4.12, the OpenFlow switch escalates the event on to the OpenFlow Controller. The OpenFlow Controller invokes further application logic, which has subscribed on an event trigger point before. One or more than one application can be invoked through such an event. In the presented case, only the modules Network Design and Flow Placement have been invoked through a request. An optional response from the application downwards to the OpenFlow Switch over the OpenFlow controller enforces policy decisions affecting the data path.

In comparison to bursting file-download or website invocations, video streaming might remains as a significant factor in the network for a longer duration with real-time requirements on the Service-Data-Flow (SDF). Therefore we specified and developed the Network Design & Active Flow Placement Module for (first) computing the network design in a near optimal scenario using approximation with graph theoretical approach and (second) identifying the QoS class per flow and applying a specific routing schema on the SDF.

The aim of the **Network Design Module** is manifold. The number of active network elements should be limited to reduce the energy consumption of the network. Overload situations in the network are avoided. The overall throughput is maximized by spreading the data traffic equally through the network while meeting minimum delay constraints at the same time. Bottlenecks are avoided with our GARC network design approach.

The mathematical NP hard network design problem is defined as follows. The full network topology is predefined as a graph G=E,V using edges (E) representing connections between network elements and Vertex (V) representing switches. Vertexes are initialized with parameters indicating the ability to temporarily remove or suspend a selected vertex from the routing topology for energy savings. Edges are initialized with maximal bandwidth constraints as costs and all switches are connected at least to one controller. The Network Design and Adaptive Flow Placement Module computes an initial network design which is adapted to the real-time network load situations continuously in predefined cycles. New established connections are taken into consideration; terminated flows are excluded from the graph.

Overload situations on particular network vertexes indicated through real-time network statistics towards GARC influence the network design decisions. GARC and the Network Design algorithm specifically enable elasticity to the network topology through enabling or deactivating network elements according to the network utilization. Network efficiency as well as resource- and costs-savings are the benefit of this approach.

The second important and novel aspect is the fine granular per flow prioritization and **active Service Data Flow Placement Module** or re-routing through graph theoretical methods.

The Adaptive Flow Placement Module determines the routing method in an individual per service-data-flow manner. The module uses groups and aggregations of flows for simplification and reduction of the complexity.

Figure 4.13 depicts the signaling request message starting from the network towards GARC indicating a new Service-Data-Flow (SDF). Each packet-in event in OF Switches for new established SDFs query routing decisions from the OF Controller immediately. Our approach excludes routing decisions from the controller

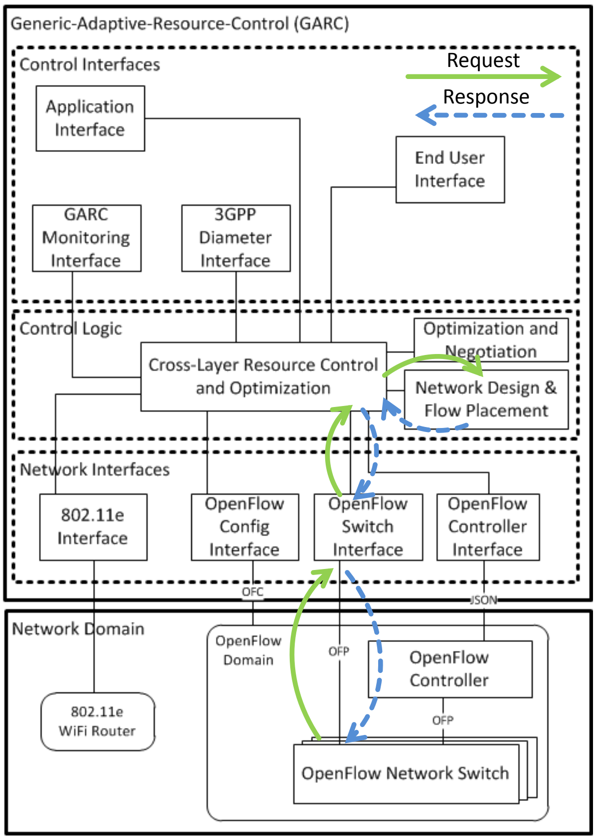

Figure 4.13: Flow Placement Signaling Data Flows between GARC and OpenFlow

into the GARC Network Design and Adaptive Flow Placement Module specifically. This module authenticates and authorizes the user, given the TFT of the SDF based on the end-user IP address using the Diameter Sp interface. The service is identified using the service IP address and port within GARC, optionally once registered.

After mapping the SDF to a QoS level derived from the user profile, the active service-data-flow-placement module computes the optimal data path. SDFs with a high QoS level are routed using 'shortest path' algorithms (e.g. Dykstra). Medium level of QoS results in 'equal network load' or 'minimal network element involvement' or 'hybrid routing variants'. GARC policy constraints ensure a maximum delay overhead for non-shortest path routing e.g. shortest path plus 10 percent. Such constraints are predefined and adaptable over the GUI by the network operator or service provider during runtime.

The network design module communicates with the OpenFlow domain using the OFConfig protocol. The Flow Placement Module communicates with the OpenFlow Domain over the OpenFlow Protocol.

4.5.6 Software Defined Telecommunication Network Domain

A general model for Software Defined Telecommunication Network with Cross Layer control functionalities using OpenFlow and 3GPP Evolved Packet Core (EPC) is elaborated in the following. Therefore a specification of the OpenFlow Switch (OFS) and OpenFlow Controller (OFC) are presented in the following two paragraphs in more detail. The OFC is designed to expose control functionalities over a northbound reference point towards GARC or other non-network-aware applications. The OpenFlow Protocol features are used in version 1.4.0 without further modifications to ensure standard compliance.

This subsection starts outlining the most relevant aspects of applying an architecture split of EPC towards Control plane and OpenFlow enabled User-data plane. The Control plane might be hosted in a data center and is characterized by redundancy, flexibility and the ability to be deployed from User-data plane network elements. The User-data path is limited to fixed network operator infrastructure components to ensure performance, but exposes control APIs towards the controller.

The OpenFlow is used as a Cross Layer protocol in between the user-data plane and control plane.

Several components handle IP data traffic of bearers besides control messages in the current 3GPP Rel 11 EPC architecture. The PGW is the breakout gateway towards external IP networks and provides filtering, gating and policy enforcement functions on the bearer. The SGW routes IP packet data according to APN and is the bearer path anchor of the UE on the 3GPP access network.

The new OpenFlow enabled EPC approaches published in [155, 156, 157] merges the concept of SDN with today's 3GPP EPC architecture. One basic concept behind SDN is the separation between control and data plane.

In figure 4.14 the User-data plane components SGW and PGW are shown as being further separated into PGW-C,PGW-U and SGW-C,SGW-U.

Such a split enables a higher level of flexibility as the amount of SGW-Us can now be adapted according to current network load situations and real-time network requirements. This Cross Layer concept opens up new ways to develop energy aware networking and elastic network topology design [42, 40].

Software Defined Telecommunication Switch The Software Defined Telecommunication Switch should support fast IP packet processing and ensure high reliability. In Figure 4.15 the basic architecture of the enhanced OpenFlow Switch is shown by presenting its three key components. These are the OpenFlow (1) pipeline for chaining lookup tables, (2) ports for managing egress and ingress of IP packets and (3) the OpenFlow channel between OFS and OFC.

The pipeline includes ordered flow tables with a numerical identifier, which are linked through GOTO-TABLE actions. Each packet enters on flow table 0 and is only allowed to be handed over another flow table of a higher identifier to avoid packet circulation. The flow tables consist of a priority and a variable amount of flow entries for packet matching and actions. A flow entry contains matches which

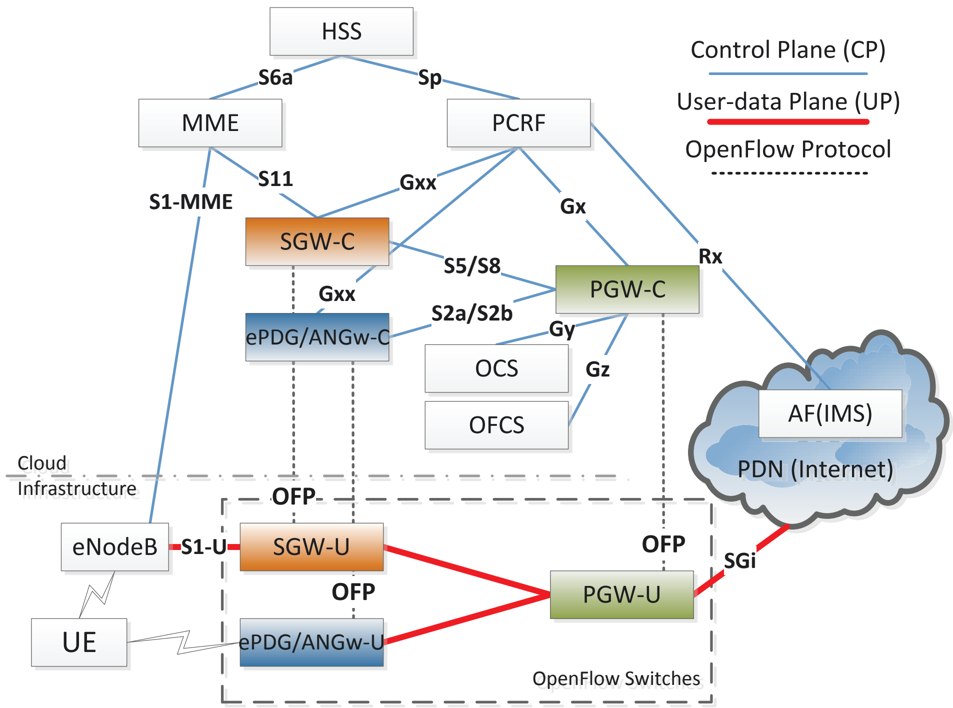

Figure 4.14: OpenFlow Enhanced 3GPP EPC Architecture Split

compare the packet header with the matching part of the entry. The flow entry also contains instructions and actions which tell the switch how to process the packet.

Second architectural component of the switch is the port. Ports represent interfaces to the network and can be used for sending and receiving packets. There are two different kinds of ports described in [13], which are physical and logical ports. Physical ports correspond to a hardware interface of the switch, and logical ports are high level abstractions that implement additional functions (e.g. tunnels, loop back interfaces, packet encapsulation). The packet processing on these ports must be transparent to basic OpenFlow processing.

The last main switch component is the connection to the OpenFlow controller represented through the OpenFlow channel. The connection to the controller is based on the OpenFlow Protocol.

Figure 4.15 depicts in which order a packet is processed within the switch architecture. The flow of the packet through the depicted components is marked with the black solid arrow in the figure. This example describes a packet arriving on the physical interface eth0 and matching the first flow entry in the flow table 0. Flow table 0 is the first table a packet has to pass. This table 0 and every following table consist of a table-miss entry which takes care of unmatched packets. In this example,

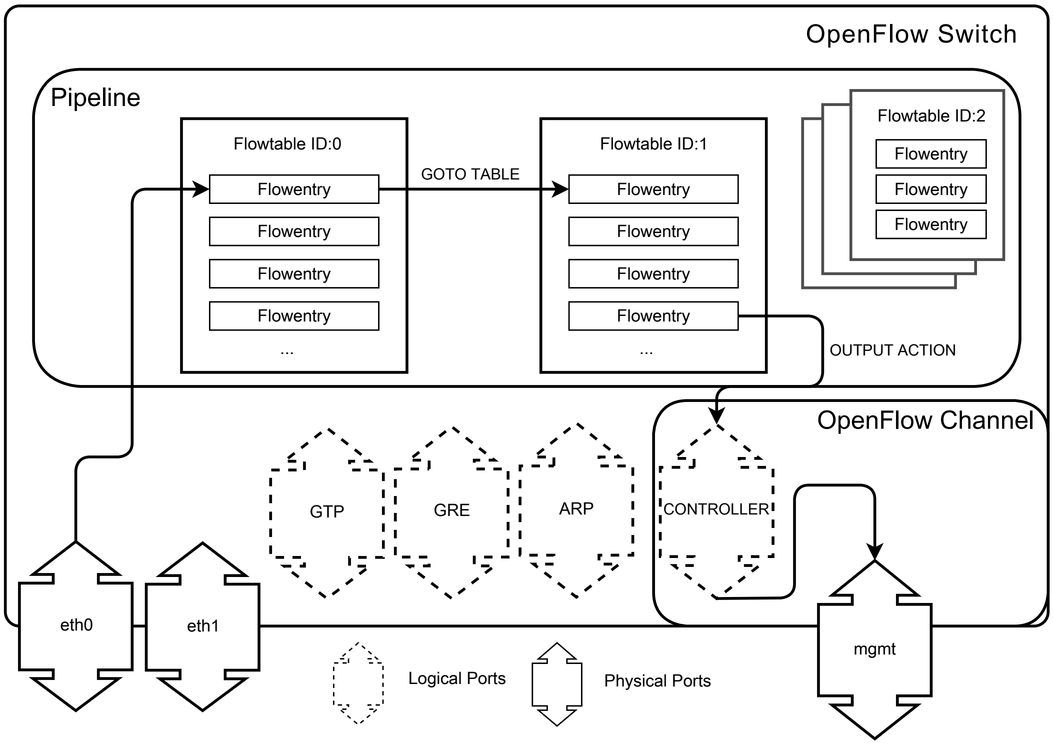

Figure 4.15: OpenFlow Switch Architecture

the first flow entry matches the packet and processes a GOTO-TABLE instruction to flow table 1. The next flow entry forwards the packet to the controller.

One improvement of this OpenFlow Switch architecture is the GTP and GRE packet processing ability.

The switch provides the logical ports for encapsulation and decapsulation of the packets. The example of processing of translating GTP packets from one tunnel ID to another is shown in Figure 4.16 in detail.

After a packet arrives on a physical port according to the matching of the UDP-port (GTP) or protocol header field number 47 for GRE, it is forwarded to the corresponding decapsulation port. Now it is possible to determine the tunnel id of that packet. Independent of the underlying tunnel protocol the packet now consists of the IP header plus transport layer header plus payload. From now on it is also possible to send the decapsulated packet on the wire as long as a MAC header is added. In our example we will translate tunnel ids. The following flow table (TEID) holds matching entries to execute the translation. It is also necessary to add a meta data field, which contains the identifier for the corresponding destination tunnel IP. The next step of the tunnel id translation is the encapsulation. In this part the header structure of the final output frame will be added to the packet. It is necessary to fill this header structure and therefore the flow table (METADATA) comes into play. Based on the decapsulation port, the network layer and the link layer will be set. This is done by the set field actions of the specific flow entry. An important objective of our architectural pipeline design is to keep the need for non-standard functionality in the OpenFlow switch to a minimum. This results in the current pipeline design, which uses only the matching fields and actions/instructions defined in the OFP standard. Other than the logical encapsulation/decapsulation ports for GTP/GRE, the OFS does not require any kind of additional functionality other than what is specified in [13], in order to function as part of the OpenEPC User-data plane.

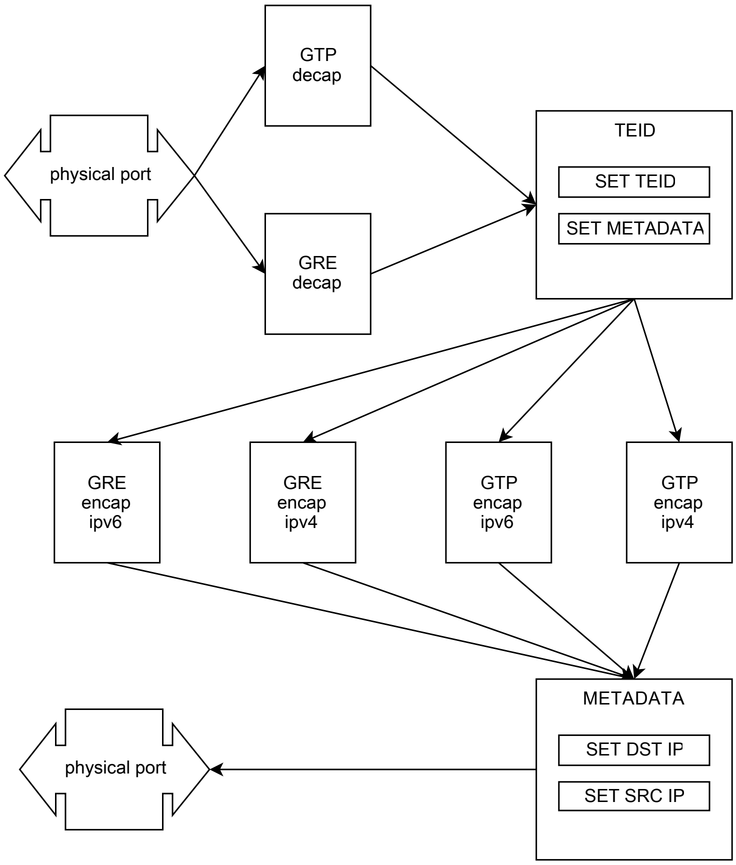

Figure 4.16: OpenFlow Switch GTP/GRE Pipeline Design

Another additional feature of the enhanced OpenFlow switch is the integration of Address Resolution Protocol (ARP), which is used to resolve network layer addresses into link layer addresses. In our case we need to configure more than one IP address to one physical interface. To resolve the IP addresses accordingly, ARP requests are sent to the logical ARP ports. Typically this functionality is handled by the controller (e.g. forwarding.l2-learning in pox [158]). With this approach we achieve shorter delays, but it also solves another important drawback, which has its origin in the encapsulation process of logical ports. It is necessary to determine which mac address a remote host is dedicated to. Therefore the switch handles a ARP cache table and upon missing cache entries, an ARP request is flooded to the ports.

Software Defined Telecommunication Controller The OpenFlow controller is the intermediate layer between network applications and OpenFlow switches. In our presented concept, the controller is based on a three-tier architecture shown in Figure 4.17. The three key components of the controller are (1) the core function layer, (2) northbound interface and (3) southbound interface.

The southbound interface handles the communication with OpenFlow switches using OpenFlow Protocol. It consists of two components: the OpenFlow channel and OpenFlow message codec. The OpenFlow channel connects each switch to the controller. The OpenFlow message codec, as its name shows, is used for encoding/decoding each time a message needs to be sent or received.

The core function layer contains a minimized set of functions required when deploying a controller. The controller-to-Switch Message Pusher constructs new messages and push them to the OpenFlow channel. For asynchronous and symmetric messages coming from the switch, the corresponding message handler will be invoked, which pre-processes the message and dispatches it to functions in a northbound interface or other user defined applications outside the core space.

The Channel Manager takes the responsibility for establishing and maintaining OpenFlow sessions with switches. The selection of carrier protocol (usually TCP or TLS) and the OpenFlow handshake procedure are all done here.

The northbound interface is the key enabler of network programmability. Functional components such as PGW-C and SGW-C in our EPC architecture can be deployed as higher-layer network applications upon the controller. The Switch Agent allows users to communicate with the switch by sending and receiving OpenFlow messages. It is a direct map of core functions, but with more well-defined API and much more flexibility. The Topology Discovery function calculates and maintains the topology of an OpenFlow network by using Link Layer Discovery Protocol (LLDP). Users are able to query different kinds of information such as connected peers, related ports and link states by using this function. The Network Design and Flow Placement component [42, 40] is designed for traffic engineering usage. It supports setting the flow path dynamically and shaping traffic according to specific routing rules and policies. All these functions are exposed through the local API in our OFC architecture, with which (Cross Layer network-aware) applications can be designed and developed locally on the controller platform. Additionally, to meet the requirements of decoupling applications from the controller, a set of network API is provided. The controller runs an API server to handle incoming requests from remote network applications.

The presented open design enables network developers to develop applications by using two different kinds of API exposed by the controller. With the local API, applications are hosted in the same machine as the controller, and use the same programming language. However, it is not always the case that the application and controller are kept in the same environment. Thus, as an alternative solution, the network API provides the possibility for remote communication. The controller runs an API server to handle incoming requests from other network applications.

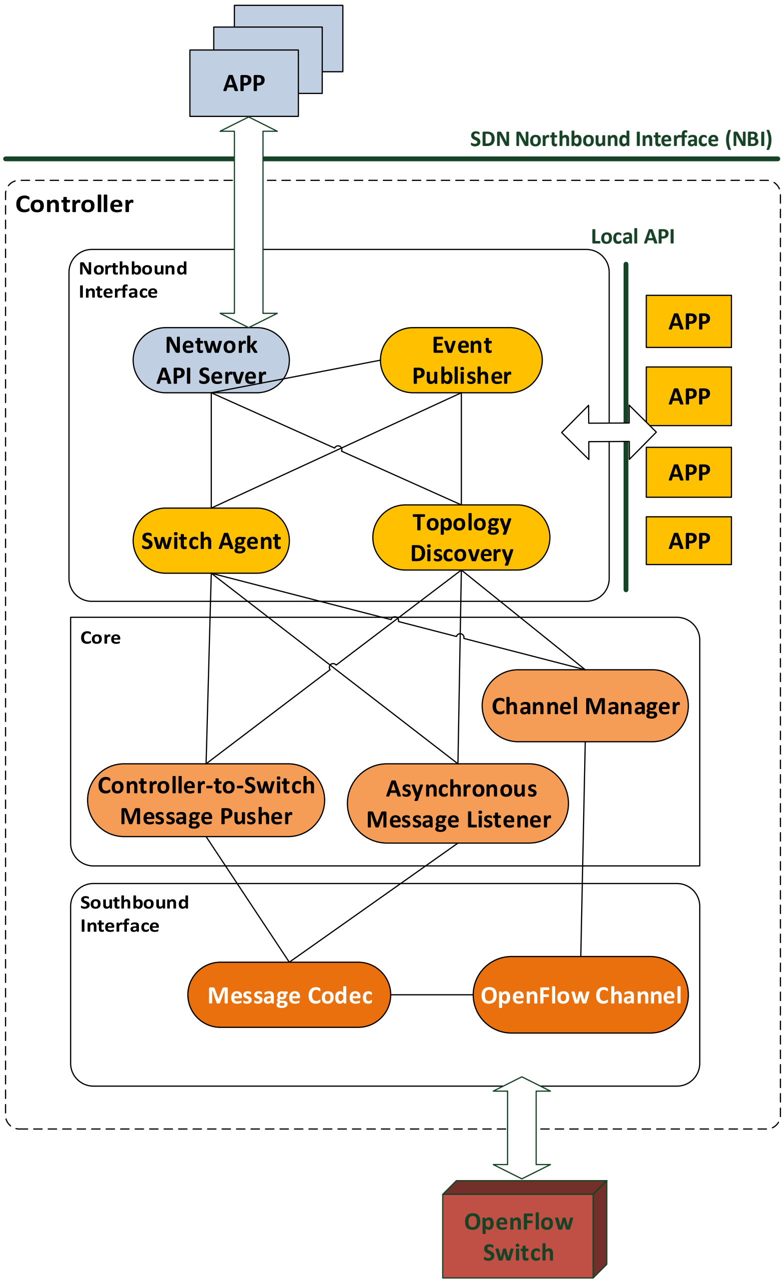

Figure 4.17: OpenFlow Controller Architecture

4.6 Cross Layer Optimization Architecture Reference Point Specification

The following section specifies the six key reference points for the Cross Layer Optimization Control architecture.

Four domain specific and two optional reference points have been defined. The domain specific reference points are connecting GARC towards:

- User Equipment (UE), device or end user further outlined in 4.6.1
- Service Provider and Network Operator infrastructure Business Support System or Operational Support Systems (BSS/OSS) further outlined in 4.6.2.
- Service or server side application further outlined in 4.6.3.
- Transport network infrastructure further outlined in 4.6.4.
- Monitoring (as an optional reference point) further outlined in 4.6.5.
- Network GARC-GARC (as a horizontal optional reference point) further outlined in 4.6.6.

4.6.1 End User Domain Interface

In the following, the optional interface towards the end user or device, as depicted in Figure 4.7, is specified for enhancing the connectivity further.

This reference point is regarded as optional, because existing and already installed services or applications on an end user device will not be modified to support this additional functionality. Rather it is intended to provide an additional function on the end user devices, which allows the signaling of QoS related information.

Additional information derived from three main layers on the device are exposed: application layer (user interaction, multimedia CODEC usage, application information, video buffer state, etc.), operating system layer (device information, battery status, network interface list, etc.) and network layer (packet loss ratio, link status, IP address, port, active network interfaces, etc.).

From a conceptual point of view, a trusted extra signaling functional block on the UE lists all active connections and supports an easy prioritization based on user preferences.

Each entry on the list contains a Traffic-Flow-Template (TFT) identifying the source and destination IP address and port, together with protocol information.

Such a list is signaled over the GARC-to-Device-Interface back towards GARC using REST interface through the extra signaling application initiated by the end-user. GARC authenticates and authorizes such signaling request messages. Alternatively these lists can be managed over a web portal by the end-user. Additionally, the 3GPP S14 reference point between UE and ANDSF transports connectivity map information over the S14 interface using SyncML and OMA DM protocol formats.

Two modes of operation have been defined for mapping application type and QoS class. Firstly, the user is enabled to dynamically signal QoS parameter modification requests into the system. This situation might be the case, when the received QoE/QoS is lower than the expected QoE/QoS by the end user customer. Secondly, the customer is enabled to define the QoE/QoS mapping per application or application type via a web front-end in a static way.

4.6.2 Service Provider and Network Operator Domain Interface

A 3GPP specified Diameter [63] reference enables the communication between GARC and the network operator and the service provider environment over standardized interfaces. In particular the Diameter protocol ensures Authentication (verifying the identity of an entity), Authorization (granting or revoking access to a resource) and Accounting (collecting information on resource usage for billing, auditing or cost allocation) [159] with the referring operator Policy and Charging Control (PCC) Architecture.

This Diameter interface might be used for several purposes. A Subscription-Profile-Register (SPR) in a mobile network stores user related information. This can either be dynamic information such as tracking-area, assigned IP address(es), active subscriptions, etc. or static user information such as QoS profile, personal information, etc.. According to the 3GPP standard, the SPR or Home-Subscriber-Server (HSS) within the IP Multimedia-Subsystem (IMS) are queried over Diameter Sp or Sh reference points. The Diameter Sh [160] reference point enables user profile validation, user demanded QoS requests and is connected to GARC.

In addition to PCC services, the Access-Network-Discovery-and-Selection-Function (ANDSF) is queried by GARC over the S14 interface to determine networks in the adjacency of the terminal and to perform vertical handover optionally.

3GPP standardizes the Traffic Detection Function (TDF) as a transparent functionality (standalone or hosted on a gateway) within the network providing internal characteristics of the data flow. External IP packet parameters (such as source or destination IP addresses or ports of known Internet services) or Deep-Packet-Inspection (DPI) to retrieve packet internal header- or body-information may be used to identify a specific Service-Data-Flow (SDF). The 3GPP specified Traffic-Detection-Function (TDF) analyzes IP data traffic characteristics, IP and port combinations in order to gain knowledge about the underlying traffic and its related requirements. TDF is a cost intensive functionality, even when it comes to Deep-Packet-Inspection (DPI) in core network elements, when the packet body is analyzed in real-time. Limitations and challenges of TDF in general and DPI in particular include encryption e.g. by tunneling IP in IP data traffic through a Virtual-Private-Network (VPN).

The TDF assists in enriching requirements of service data flow, which have not been signaled during service invocation. The TDF should be regarded as an external network component, which is able to analyze traffic based on known traffic signatures and characteristics. Once an IP data flow is identified successfully, the TDF is able to signal the flow meta data towards the subscribed entity for further processing.

The 3GPP defined Traffic-Detection-Function (TDF) is used to provide passive information about a given data flow by analyzing IP data traffic characteristics, IP and port combinations in order to gain knowledge about the underlying traffic and its related requirements. The use of TDF enables backwards compatibility for classic IP services, which are not able to communicate their level of QoS in a proper way. A TDF residing in a gateway may inform GARC about bearer establishments, modifications or termination. Indications for a TCP connection setup (3-way-handshake) or the termination through SYN/FIN packets may be used. An open problem is the clear identification of tunneled or encrypted traffic.

3GPP standardizes the TDF further as a transparent functionality (standalone or hosted on a gateway) within the network providing insides of the data flow characteristics. External IP packet parameters such as source or destination IP addresses or ports of known Internet services or Deep-Packet-Inspection (DPI) to retrieve packet internal header- or body-information may be used to identify a specific service data flow.

TDF is a cost intensive functionality, even if it comes to Deep-Packet-Inspection (DPI) in core network elements, when the packet body is analyzed in real-time. Limitations and challenges of TDF in general and DPI in particular is encryption e.g. by tunneling data traffic through a Virtual-Private-Network (VPN). As an un-trusted party of the communication, the client should not be regarded as independent and trustworthy information source, but the network is regarded as such.

Offline and online charging is supported over existing interfaces from the core network towards the OCS and OFCS.

4.6.3 (3rd-Party) Service Domain Interface

The (3rd-Party) Service Domain Interface depicted in Figure 4.7 is a bi-directional reference point providing a secured connection between any network-aware 3rd party service and GARC. This interface is optional and enhances the Cross Layer model of GARC in the network operator and service provider domain further. Using that reference point, applications are enabled to register their service as a set of supported QoS levels at GARC. The exposed parameters are meant to be controlled by GARC externally. One example and usage scenario is an adaptive video streaming server as described in the evaluation section of this thesis, which communicates its available server source IP addresses, CODECs, frame- and bit-rate together with the supported bandwidth towards GARC. GARC assigns each service a unique Application-Function-ID, which is stored in a data base together with other information exposed by the service.

An initial registration process creates the peering between any network-aware service and GARC. The GARC Application Interface transports service control messages from GARC towards the service. Reasons for such a signaling are QoS/QoE degradation measurements due to high network bandwidth utilization or overload situations at the service side. The GARC Cross Layer Resource Control and Optimization Module queries a policy decision from the Optimization and Negotiation Module that might result in service rate adaptation.

A service might be a 3rd-party-service or an operator controlled Service-Delivery-Platform (SDP) in this regard. A bootstrapping mechanism registers the service itself together with a set of parameters to GARC automatically upon start-up. Network-aware multimedia services are enabled to signal a list of supported CODECS, bandwidth level including guaranteed and maximal bandwidth, bit rates, frame rate and resolution towards GARC. Overload situations in the network might cause service adaptation through GARC in turn, to ensure seamless communication instead of service interruptions.

4.6.4 Network Domain Interface

At the time this thesis was written, there was no common network interface standardized in all open network technologies. The 3GPP 4G telecommunication network exposes dedicated control interfaces for QoS control. Since 4G is been rolled out recently, the Rx interface is not widely used. The Software Defined Network exposes northbound interfaces for routing and path control within virtual networks. The northbound interface was also not standardized at the time this thesis was written, but in turn defined depending on the underlying controller, which also varies due to the large amount of available software solutions [161, 162].

Even other networks are closed and do not offer any control mechanisms towards the upper layer. As addressed in the related work section 2 in more detail, the Evolved Packet System specified the Rx-reference point [64, 71]. The Rx interface enables the communication between the Application Function (AF) and the 3GPP PCC architecture through signaling QoS specific parameters over the Diameter protocol. 3GPP defined subscribe and notify mechanisms [66] report network events (loss of bearer, guaranteed bandwidth violation, bearer modification, etc.) to the PCRF, which in turn notifies all subscribed applications.

Next to the model depicted in Figure 4.7, we've specified in-network packet-loss measurement functionality, which reports link quality in form of packet-loss ratio towards GARC. Such monitoring information is extracted from NodeB, eNB, Access-Points, routers and OpenFlow switches towards GARC.

GARC to Network Interface Layer The GARC enables the telecommunication system to react appropriately to measurements on the data path. The GARC logic presented in 4.5 further elaborates on the Cross Layer Optimization process, which involves network measurements addressed in this paragraph. The goal of the optimization process within GARC is to identify a set of possible actions. These actions are validated in terms of their costs and security policies. Finally, either no decision is made or one solution is selected as an optimization. One of the results of such an decision caused by an action is to support and enable vertical handover between heterogeneous access networks into adjacent networks. The handover might be performed, if the target network offers more suitable network conditions in form of channel quality, less costs for the operator or the customer or simply is less loaded.

Figure 4.18 depicts the interaction between Generic-Adaptive-Resource-Control (GARC) and other telecommunication system related components involved in QoS control. GARC specified to be align to the 3GPP PCC architecture and extends it in the way that either user or service initiated requests (Rx#), real-time network traffic situations (Sd), service utilization and context information (Sp) are used as input parameters for the decision logic within GARC. The most suitable and optimized policy enforcement strategy given for a specific network is determined within an optimization function of GARC and finally enforced (Gx#/Gxx#).

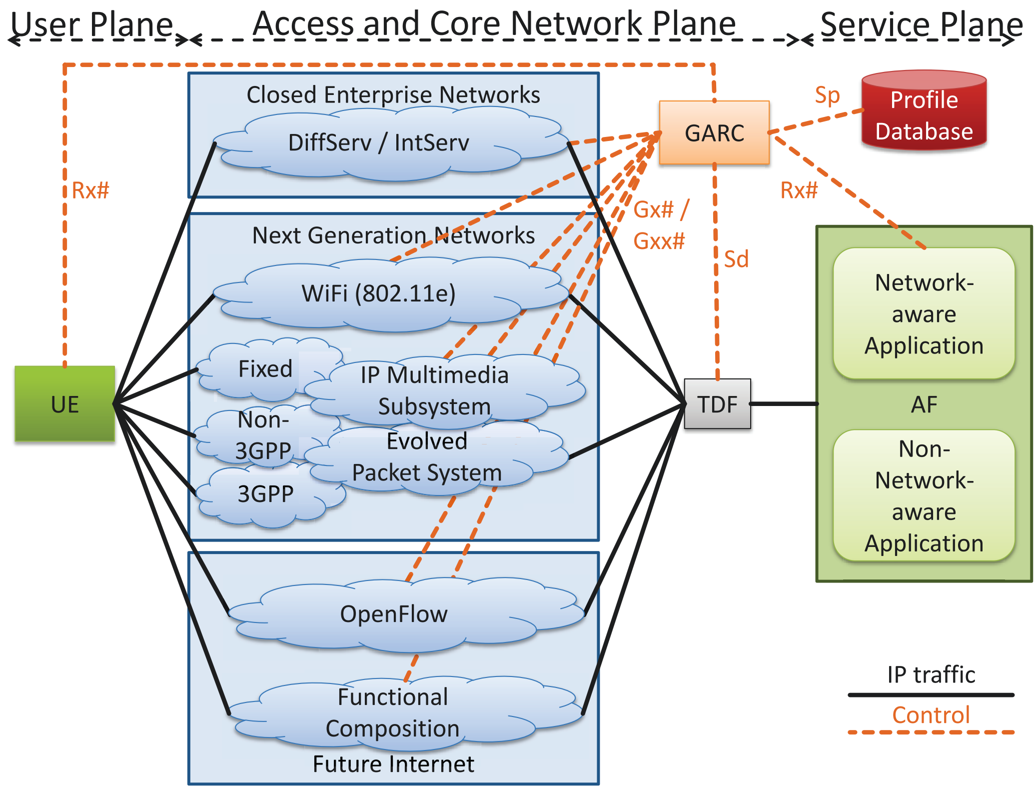

Figure 4.18: Multi-Network Support of GARC

Our approach with GARC extends the 3GPP PCC, but is backwards compatible with EPC and LTE at the same time. Innovative QoS optimization functionalities are specified to extend the functional spectrum towards WiFi IEEE 802.11e and OpenFlow. For OpenFlow we extended the concept of OpenFlow Controller and Switches for introducing queues for different QoS levels and expose real-time network measurements at the same time towards GARC. For IEEE 802.11e we specified a packet labeling mechanisms, which is either logically located on the Access Point (AP) or transparent on the data path and modifies the Type-of-Service (TOS) field in the Internet Protocol (IP) header according to the importance of the application.

One key aspect of GARC is the generic design, through which any QoS-supporting access- or core-network or data center can be attached to GARC by implementing a driver-like adapter. An adapter translates generalized QoS signaling parameters into network specific QoS parameters and vice versa. As a first set of adapters, we've designed and developed adapters for WiFi IEEE 802.11e, SDN adapters supporting Stanford OpenFlow Protocol and 3GPP Diameter Protocol. Other adapters (e.g. for WiMAX) are possible, but are beyond the scope of this thesis.

SDN / OpenFlow Interfaces The ONF definition of a northbound interface on top of an OpenFlow Controller in working groups is still under discussion. In addition, the OpenFlow Configuration and Management Protocol (OFconfig) in version 1.1.1 [163] is specified by ONF. OFconfig supports configuration and management of OpenFlow domains consisting of multiple switches and controllers. OFconfig enables topology management and connectivity control between switches in the long term, while OFP supports ad-hoc queries for time critical routing decisions. The topology in regard to connectivity is controlled over the interface, too.

The OpenFlow Controller Interface abstracts from various OFController implementations and provides a generic concept to control and manage certain OFController functionalities. These are:

- Extract network topology information (switch statistics).
- Enforce switching and routing decisions of Service Data Flows computed in GARC.

Interoperability to many other OF-Controller and OF-Switches is ensured by using OF Protocol and OF Config in the heterogeneous OpenFlow software and hardware ecosystem [161, 162].

The OpenFlow switch interface of GARC connects to the OpenFlow switch via OFP. The OpenFlow switch interface enables GARC to query real-time network statistics (packet-loss, packet-drop or data rate statistics of each switch) and to retrieve notifications of packet-in events on switch level, what e.g. triggers a routing decision in the controller or novel dynamic flow placement.

The OpenFlow Controller interface of GARC connects to the OpenFlow controller over the - at this point not standardized - northbound interface. The routing decision module has been extracted out of the controller into the GARC Flow Placement module presented above and depicted in Figure 4.13. Our approach to the northbound interface is aligned on the 3GPP Diameter Rx, Gx and Gxx reference points between Application Function, PCRF and gateways.

Two communication modes are envisioned in GARC. The button-up operation mode extracts information out of the network event and signals them through the OF Controller towards GARC. The top-down operation mode first computes policy decisions within GARC. Once computed, GARC pushes them down into the network actively.

The button-up approach exposes network statistics out of the OpenFlow network towards GARC. Top-down approach pushes QoS level decisions for an IP Service Data Flow (SDF) into the network for enforcement or computes a data path (shortest path, equal network load, minimal network element involvement, hybrid variants, etc.) through the network according to the computation from the novel Flow Placement module in GARC.

Packet-In-notifications within OF switches trigger message requests from the OpenFlow network into the OpenFlow Controller. For scalability reasons, the request is not forwarded on to GARC. The direct involvement of GARC at this point causes a bottleneck in the system and delays data path establishments further. In contrast, predefined routing patterns are computed in GARC, which are pushed on the OF Controller by GARC or even directly into the OF Switch.

IEEE WiFi 802.11e Interface IEEE WiFi 802.11 networks do not support QoS per se. While cellular networks are controlled over the centralized (e)NodeB, which schedules the airtime of all associated devices, WiFi 802.11 works in an unmanaged way. Each communicating terminal computes a random back-off time before starting with the data transmission over the shared medium (carrier sensing). In our approach to the design of this interface, we focus on the downlink traffic control, in which we assign Enhanced Distributed Channel Access (EDCA) QoS classes to the Service-Data-Flows (SDF). Still no hard QoS guarantees can be given over 802.11, but when using layer 2 EDCA 802.11e, over time high-priority traffic has a higher chance of being sent than low-priority traffic statistically. EDCA defines four QoS classes: Background (AC-BK), Best Effort (AC-BE), Video (AC-VI), Voice (AC-VO), Legacy DCF. These classes are mapped against a user profile within the GARC Cross Layer Resource Control and Optimization module and are assigned to SDF. The aim of the WiFi 802.11e Interface is to label packets on the data path based on policy decisions made by GARC. Such EDCA classes will be supported by WiFi access points with 802.11e support.

We are not including the uplink data path, because additional modification of the packet buffering and scheduling are required. As stated in the requirements section 3, the presented solution of GARC should work with minimal modification and should be backwards compatible.

3GPP Evolved Packet Core Interface The EPC has been interfaced using the Diameter Rx reference point. A diameter peer is conceptually integrated into the network adapter layer, which interacts with the 3GPP telecommunication domain.

In order to enforce network policies created through the PCRF, the policy enforcement function has to be specified.

As part of this thesis, a QoS module for the EPC gateways, the PGW and SGW have been specified as follows.

Several schedulers for QoS support have been analyzed and compared, as outlined in C.2 of the Annex.

The routing extension modules routing_raw, routing_encap, routing_gtpu, and routing_sndcp handle the input-output at the physical interface or at the end of a tunnel. These modules are the interfaces to the networks that are separated by the gateway. Packets arrive through one extension and leave through another one. The extensions accept incoming packets and pass them to the routing module, where they are classified: the routing module analyzes the header fields of the packet (protocol, source and destination IP and port) and requests the matching PCC rule and the SDF flow from the routing_pcc_sdf module; based on the PCC data, the routing module identifies the client and the bearer, determines the QoS parameters

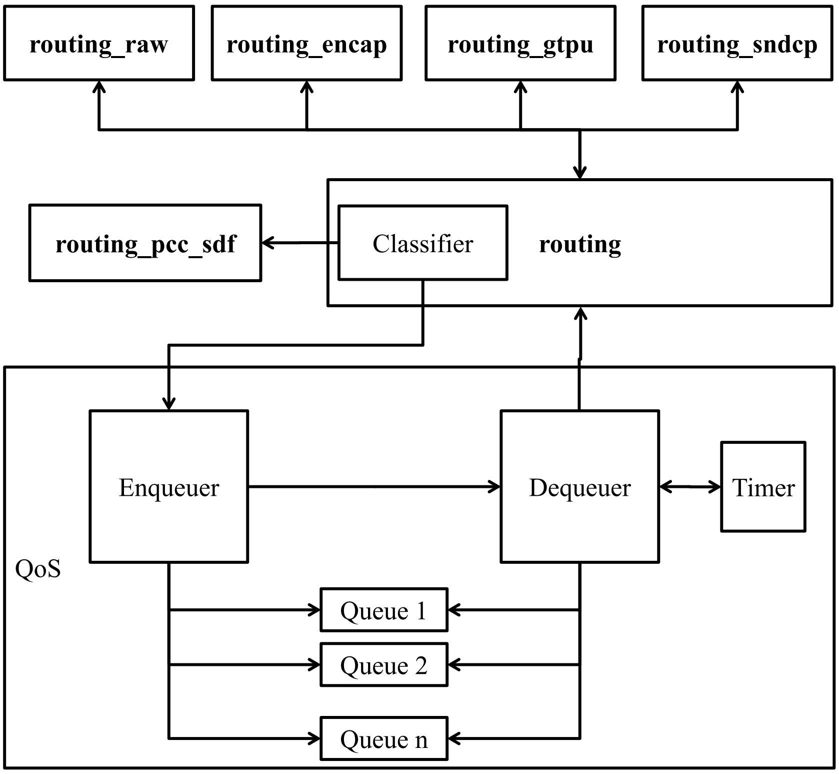

Figure 4.19: QoS Module for 3GPP Evolved Packet Core

for the flow, whether the flow is uplink or downlink, and which routing extension module should be used to send the packet to the destination.

The analyzed packets and related information are passed to the QoS module. The enqueuer selects the queue for the given bearer ID and adds the packet at the end if it is possible, otherwise, if the queue is full, the packet is dropped. Then the dequeuer checks all the non-empty queues in the order of priority and determines, which ones can send their packets without violating the restrictions. The conforming packets are sent on through the routing module. If there are still some packets that don't conform, the module calculates the time until the next packets satisfy the requirements, and notifies the timer process. The timer sleeps until the end of the timeout or a new packet arrival and starts the dequeuer.

The QoS module contains two sets of queues, one for uplink and one for downlink traffic. The uplink and downlink don't interfere. Each queue contains a list of queued packets, two token bucket counters, and two rate estimators. The first token bucket works with the guaranteed rate, the rate of the second bucket can vary from the guaranteed minimum to the maximum limit, depending on how much spare bandwidth is available to the flows. The spare bandwidth is distributed proportionally to the requested rate of the flows, in the order of the flows' priority. The rate estimators count the packets and the bytes and estimate the rates of received and sent packets for statistical purposes separately.

This is the summary of the steps:

1. Receive a packet from one of the source routing extension modules;
2. Classify the packet, find the destination routing extension, the corresponding PCC rule and an SDF flow;
3. Pass the packet to the QoS module;
4. Assign the packet to the matching queue using the packet's bearer ID, enqueue at the end of the list, update counters and estimators;
5. Check all non-empty queues, send the conforming packets through the routing modules;
6. If some queues are still non-empty, calculate the time at which the next packet should be sent;
7. Set the timer's timeout;
8. Sleep until the end of the timeout or until a new packet arrival;
9. Proceed to the dequeuing step.

4.6.5 GARC Monitoring Interface

Real-time network information exposed by the operator access- and core-network is used to optimize connectivity using GARC. 3GPP specified with Policy and flow based Charging Control (PCC) three components for (1) determining an external triggered policy decision based on subscriber profile information (PCRF), (2) enforce the policy decision within the access- and core-network (PCEF) and (3) monitor and report potential resource reservation violations (BBERF). GARC makes use of the exposed real-time network information, by subscribing to individual bearers.

A Graphical-User-Interface (GUI) on the service provider or network operator side exposes real-time network topology visualization. The topology includes network switches and controllers as well as edges representing connections between nodes. Network elements - such as OpenFlow switches - are controlled through the GUI through shut-down or wake-up messages. Control messages are forwarded out of the GUI over a REST interface though the GARC Cross Layer Resource Control and Optimization Module into Active Flow Placement Module, where decisions about network design and flow placement are made.

4.6.6 Home-GARC to Visitor-GARC Network Domain Interface

The horizontal Home-GARC to Visitor-GARC Network Domain Interface connects GARC instances over network borders among each other. End to end QoS requires peering agreements between operators such as Service Level Agreements (SLA) State synchronization of QoS policies.

4.7 Cross Layer System Interaction Model

One of our key innovations in this thesis that was enabled by GARC is the user interaction with the provider telecommunication system. This interaction model uses the GARC-to-Device-Interface and opens up additional revenue streams for the network operator, who is enabled to sell QoS as a Service. The approach presented here enables the user to decide whether or not to demand additional QoS in congested network situations, and in turn enables additional revenue streams for the network provider. A user can either be:

- An end-customer enhancing one particular, a set of or all streams originating or terminating from the end-device(s).
- A service provider paying for sponsored data connections for end-customers.
- A Mobile-Virtual-Network-Operator (MVNO) paying for enhanced QoS for all its business-customers to the physical Mobile-Network-Operator (MNO).

All offers might have a validity-duration and need to be acknowledged and accepted within a limited amount of time by the end-user. Additional granularity can be achieved by limiting the policies in terms of location, time and data consumption/volume per flow.

4.7.1 Network initiated QoS on Demand

The basic QoS-Offer-Answer-model as depicted in Figure 4.20 consists first of the Tenderer and second of the Purchaser which exchange the QoS-Offer and QoS-Answer between them.

The following steps have been designed for the overall interaction:

- Step 1 initiates the communication channel where the service publishes its operational QoS parameters set to GARC and the client registers at a well known GARC port.
- After establishing the IP layer data connection over TCP/HTTP or UDP/RTP in step 2, GARC subscribes to the bearer in the network and retrieves bearer related flow information out of the network in Step 3.
- High packet-loss ratio on a bearer triggers the creation of an offer within step 4 and 5. The user profile and its credentials are validated over Diameter Sh/Sp-Interfaces with the operator's core network. After granting a potential QoS enhancement through the operator PCC, the QoS-Offer-Answer model is triggered in step 7 and 8.
- The user input is validated in step 9. After user acknowledgment in step 9, online or offline charging functionality is queried over 3GPP standardized Diameter Gx/Gz-Interfaces.

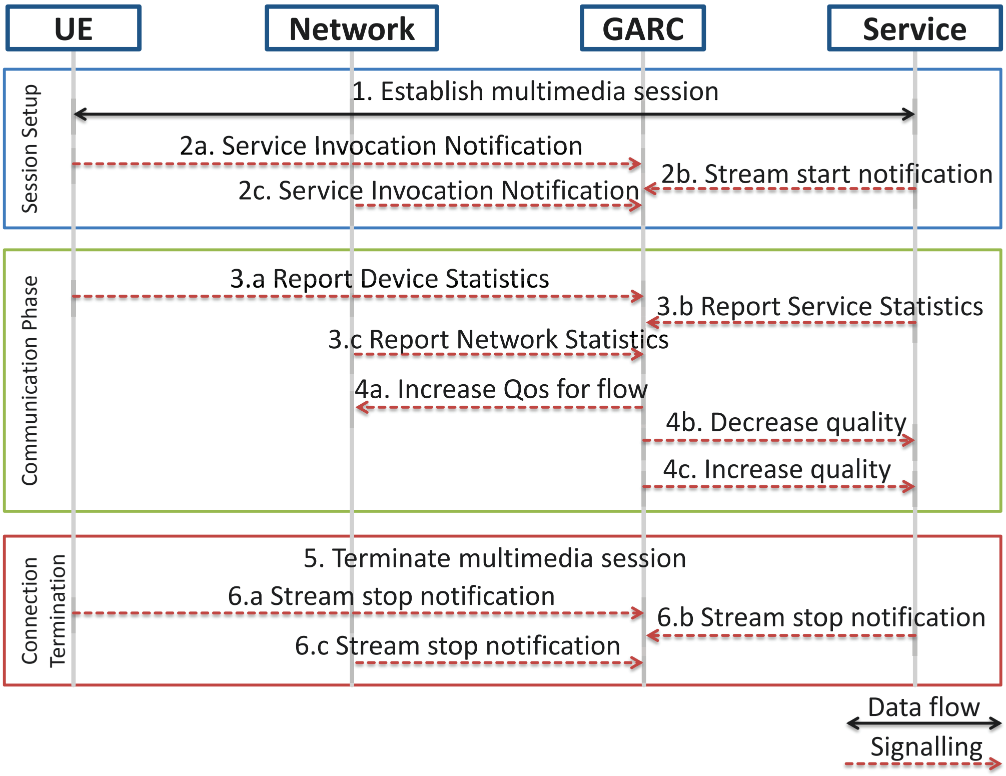

Figure 4.20: QoS Offer / Answer Model

By enabling such a Cross Layer interaction model for network driven event reporting functionality, application layer service modification is more effectively used in comparison to OTT alternatives such as Skype. Our solution supports three types of interactions: network QoS level modification, network (re)-design and flow placement together with flexible service bit rate modification.

4.7.2 Optimized Network Design - Life Cycle Stages

With Optimized Network Design a generalized Life Cycle Stages approach for inter system optimization is introduced. The life cycle is aggregated into three parts. After the initial instantiation, a monitoring control loop manages traffic pattern enforcement within the network.

1. Initialization As a first step in the process depicted in Figure 4.21, the GARC initiates the network design module and provides the network controller with a connection to the produced routing metric database.

GARC connects to the network controller in (1) and requests information about the network and its capabilities in (2). The controller gathers the available information (see Figure 4.22) in (3) and reports it back to GARCin (4). This information

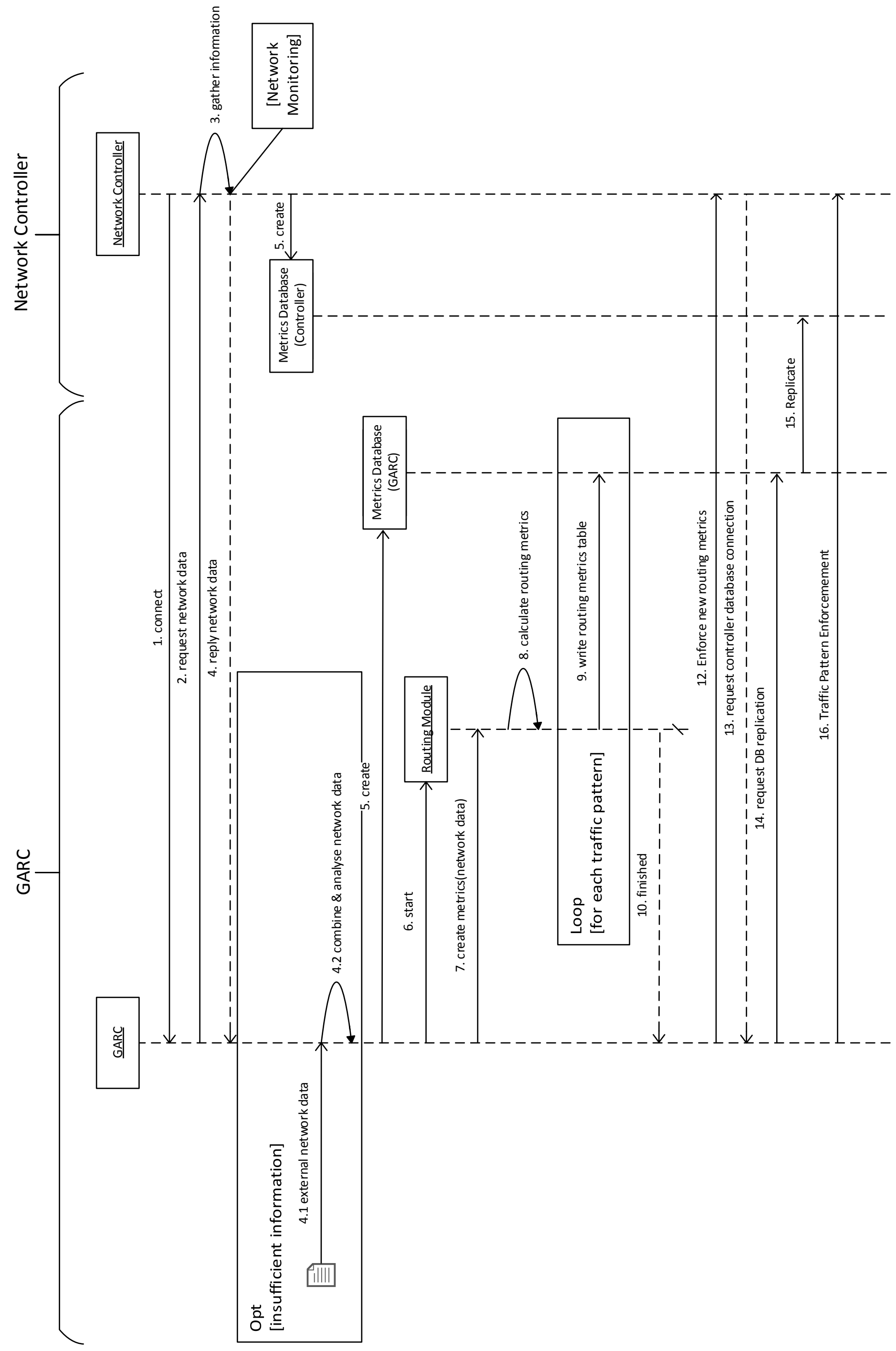

Figure 4.21: Optimized Network Design - Initiation Phase

might include auto-discovery information such as component ID, position, topology information about connectivity to adjacent components, etc.. Since there are limits to the information a controller can gather from the networking hardware (such as maximum link capacity), it is most likely that the information has to be (4.1) and (4.2) completed with the help of an external information source. After creating a database in (5) the the Network COntroller to later store the routing metrics persistently, GARC starts in (6) the network design module and initiates the metric calculation in (7) for a set of traffic templates. Point (8) triggers the calculation of routing metrics, which are then stored in the local database of GARC in (9). The network design module notifies GARC after a successful computation and storage of the routing metric storage. GARC supplies in step (11) the database access and enforces in step (12) the required traffic pattern to the controller for a given point in time. The network controller connects in (13) to the database and is able to query required metrics. The database is replicated by GARC at the Network Controller in steps (14) and (15). Step (16) enforces the traffic pattern in the Network Controller through GARC.

2. Network Monitoring Network monitoring and observation is a constant process between the controller and GARC, which runs in a permanent feedback loop. The network state is monitored in the first step, secondly the network state is analyzed, finally actions are enforced within the network, which are again monitored using step 1. Figure 4.22 depicts all relevant interactions in a sequence diagram, the individual steps of which are elaborated in the following.

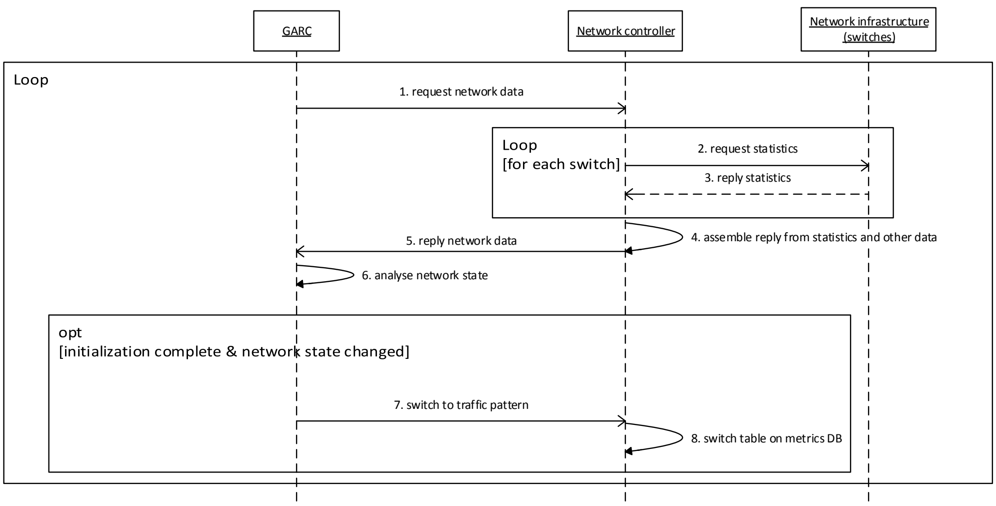

Figure 4.22: Optimized Network Design - Monitoring Phase

GARC requests updated network data from the network controller in step 1. The controller then requests statistics (2) from all connected network entities, combines

(3) and aggregates (4) the replies with the other network data it has gathered over time (e.g. the network topology). The aggregated statistics and threshold validations are sent back (5) to GARC, which then updates its internal topology map of the network and meta data. If GARC is beyond the point of initialization, it may be that the state of the network has changed (e.g. the overall network load has increased, causing packet delay or loss). In this case GARC instructs (7) the controller to apply a different set of routing metrics to the network traffic, causing the controller to request (8) its metrics from a different traffic pattern table in the metric database.

3. Traffic Pattern Enforcement The network controller instructs the switches how to handle newly detected flows. To be able to execute that in an appropriate way it relies on the metrics database supplied by the network design module.

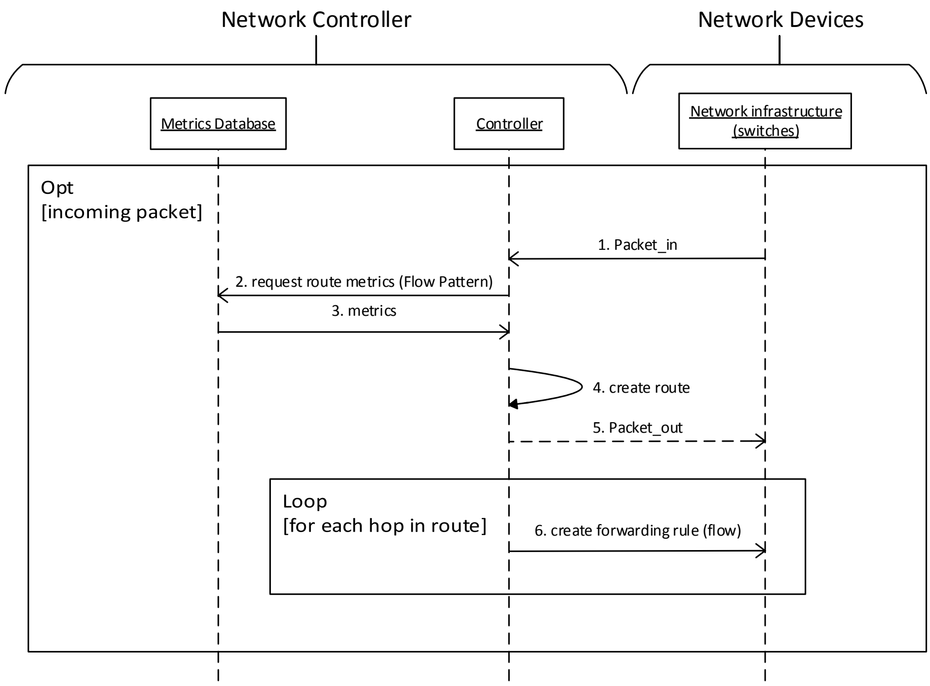

Figure 4.23: Optimized Network Design - Traffic Pattern Change Phase

Figure 4.23 outlines the message flows for traffic pattern enforcement. Once GARC sets the controller up to use a certain pattern on newly detected flows, the controller handles 1. packet-in events from a network switch, by 2. querying routing metrics from the database table of the currently active traffic pattern 3. and using them to 4. create a complete network path for the flow. A packet-out reply is then

5. sent to the requesting switch and the flow is 6. installed on all remaining switches on the route.

4.7.3 Summary

This section outlined three life cycle phases for optimizing network and application layers with GARC autonomous after setting predefining thresholds. This life cycle enables automated monitoring, policy decisions and adjustment through traffic pattern enforcement. A shorter reaction time and a state in which no human involvement is required is achieved.

The following chapter presents the implementation of the presented specification.

Chapter 5

Cross Layer System Architecture Model Implementation

This chapter outlines all parts of the GARC specification, which have been implemented in software.

Chapter 4 on *Specification* first presented a research discourse on the design aspects, followed by the presentation of a Cross Layer Reference Architecture model design and finally specified the Generic Adaptive Resource Control (GARC) function. The previous chapter includes the system architectural model, functional elements of GARC and reference points between them or towards external distributed functionalities. Major design decisions were outlined in the beginning of chapter 4 on *Specification*, which are then addressed in the design process that follows. This chapter 5 on *Implementation* outlines specific details for realizing a prototypical implementation by highlighting all major implementation decisions, selected software toolkits and the project management techniques in order to ensure a continuous development process in a team. Selected tools, programming languages, libraries, high-level concepts and design patterns applied to GARC are outlined in the following. [1]

[1] Results of this chapter have been published in [37, 38, 39, 40, 41, 144, 42, 145, 164, 146, 147, 148]

5.1 Architecture Model and High Level Function Implementation

This section outlines software technical and implementation specific details for realizing the General System Architecture and Cross Layer Optimization Functions of GARC.

5.1.1 Generic Network Adapter Layer Implementation

GARC has been designed and implemented to support heterogeneous networks. A model has been realized that transfers network technology specific resource control messages into generic resource control messages. Therefore, a generic network adapter layer for heterogeneous networks has been implemented in GARC, which mediates between network specific and generic QoS requests. In particular the various OpenFlow controllers (Ryu, Floodlight, POX, NOX and the FOKUS OpenFlow controller) have been abstracted as part of this thesis. Also an adapter for WLAN 802.11e wireless access points has been developed together with the standard conform Diameter interfaces for the 3GPP EPC.

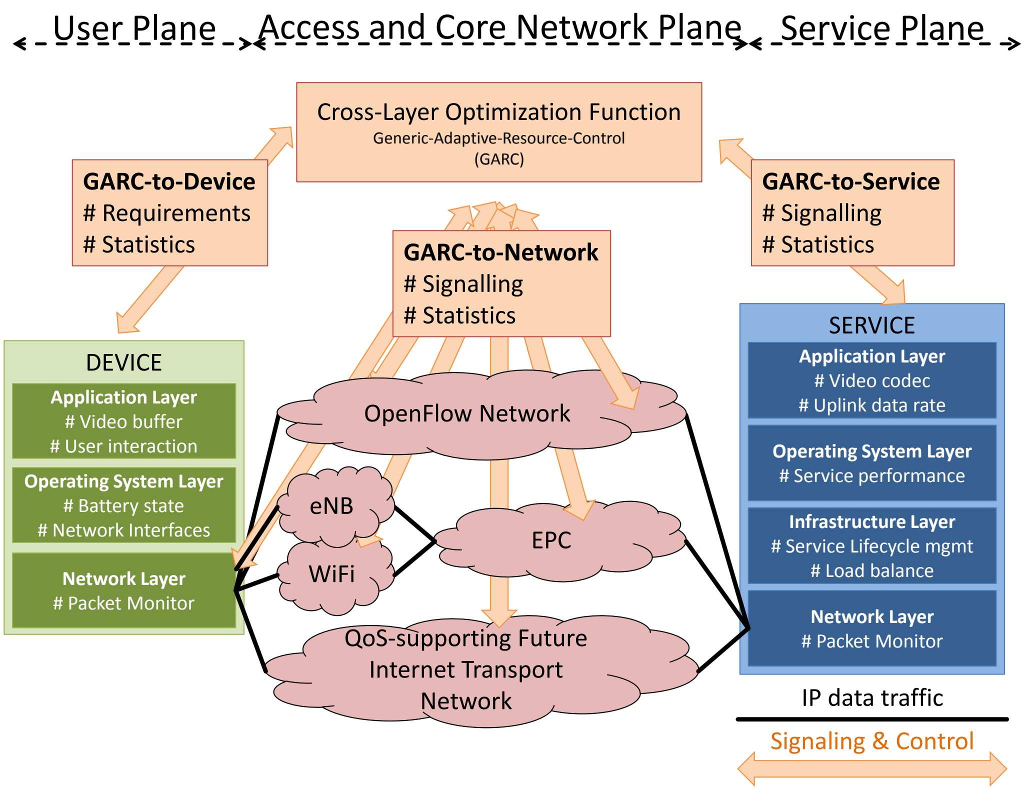

Figure 5.1: Three Reference Points of GARC

Since OpenFlow Config was specified after the first prototypes of GARC were realized, another approach was taken. A direct reference point between GARC and the OpenFlow switch has been realized without any invocation of the OpenFlow controller in the beginning. The DataPath ConTLe (DPCTL) protocol has been implemented in the adapter and GARC has directly influenced the switch parameters such as ports, queues and flow QoS levels. The controller has been bypassed in the provisioning of the OpenFlow Switch by GARC in the first versions.

Figure 5.1 depicts the three main interfaces of the Cross Layer Optimization function (namely GARC) in its software technical realization. Three interfaces providing connections to the 1) end user devices, 2) open networks and 3) (3rd-party)-services or 3GPP Application Function (AF) have been implemented aligned to the concept presented in the previous chapter.

5.1.2 Dynamic Traffic Engineering (TE) and adaptive Network Management (NM) Modules Implementation

This section presents the prototypical implementation and integration of the dynamic Traffic Engineering (TE) and adaptive Network Management (NM) modules within the Cross Layer framework, namely GARC.

Algorithms for the dynamic TE and adaptive NM modules have been implemented. In particular, a shortest path algorithm has been implemented for the adaptive Flow Placement and the State of the Art Mixed Integer Program (MIP)-solver Gurobi [165] has been selected to solve the underlying Network Design problem.

Flow routing policies and an optimized network topology have been computed as output of the algorithms. The routing policies have been applied on an OpenFlow [13] network. The interaction between GARC and the Software Defined Network over the SDN northbound interface is depicted in Figure 5.2.

An enforcement of the optimized network topology has not been implemented and has only been simulated as indicated in the following section on validation. An implementation of an NM enforcement model would be realized as an extension of the Network Interface layer as depicted in Figure 5.2.

The network topology is one of the input parameters for the Gurobi MIP-solver, in addition to traffic pattern, traffic demands and other topology meta-data information. Further details on the representation of the topology, link capacities and addition meta information are presented in [146] and in Annex C.1.

GARC queries real-time network statistics from OpenFlow Controller and Switches and thus enables Cross Layer optimizations on higher layers in turn. Real-time network utilization and predefined thresholds influence changes in the routing scheme or network design by toggling activation or deactivation of network line cards. GARC also enables, in addition to radical modifications of the network design, application layer parameter adjustments of CODEC or Service Data Rate (SDR) changes. Therefore a cost model has been defined, in which general network modifications or individual re-routing or SDR adjustments are considered. The routing schemes outlined in Paragraph 4.5.3 are pre-calculated and pushed towards the OpenFlow

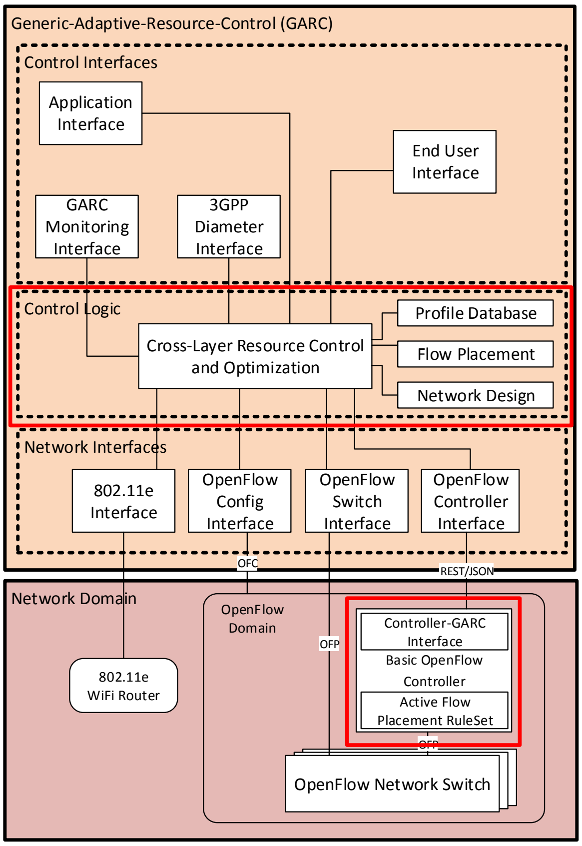

Figure 5.2: Elastic Network Design and Adaptive Flow Placement within GARC

controller actively over the JSON-REST interface depicted in Figure 5.2.

Scalability of the approach is ensured through a FlowTable Entry push operation from GARC towards the OpenFlow controllers. Therefore local network decisions can be performed without invoking further logic centralized in GARC.

5.1.3 Request Translation and Negotiation Logic Implementation

The Request Translation and Negotiation Logic has been implemented as a state machine in GARC, in which incoming notifications are analyzed and might trigger responses towards subscribed other services.

The following (non standard conform) request messages have been implemented for client (UE/device) to GARC signaling:

- 'clientNotifyStart' using parameter [flowinfo (dstip, dstport), flowid, userid] - A new service invocation is announced by the client side application towards GARC.
- 'clientNotifyStop' using parameter [flowid] - End of stream has been signaled.

FIN/ACK messages have been captured or a direct application server notification has been received.

- 'netstat' using parameters [messageid (to assign the answer), packetloss, flowid] - Packet loss ratio notification.
- 'cancelrequest' using parameter [flowid] - Terminating previous request.

Application server to GARC signaling has been realized in addition using the following signaling messages.

- 'serviceNotifyStart' using parameter [flowinfo (serverip, dstip, dstport), qualitylevels (min, max, start), parameters: bitrate (min, max, start), framerate, resolution, msgid, flowinfo] - Application Function initiated start of service notification. Can be in parallel to the client based variant.
- 'fail' using parameter [msgid, flowinfo] - Failure in adapting the flow parameter. A mediation in GARC is trigged, which leads to another request with modified parameters.
- 'ok' using parameter [msgid] - Acknowledgement of requested flow parameter.
- 'adjustquality' using parameter [msgID, flowinfo (dstip, dstport), attributes:bitrate, resolution, framerate] - Service initiated modification of the service data rate.

The negotiation logic is the central decision and control element of GARC. It has been implemented to support basic functionalities, but can be easily extended by other functionalities or substituted through cognitive decision elements, algorithms and/or dictionaries describing resources in a unified manner.

The negotiation logic has been realized in an event-driven way to be as real-time agnostic as possible. The input parameter for GARC can be service specific. All incoming parameters are aggregated, processed and analyzed against system internal policies. Section 4.3 lists all supported input parameters, which have been integrated in the policy decision process.

A variable periodic bandwidth probing from the network has been implemented. Five seconds have been proven to provide stable results in the test environment.

A variable state stabilization cycle has been introduced to avoid oscillation of the system. Four cycles have been defined for waiting until influencing the system again.

5.1.4 External Flow Control Management Function Implementation

An external network design and traffic engineering control function has been implemented through a Graphical User Interface (GUI) that enables creating, deleting and modifying flow table entries on the network entities.

Not all flows have to be managed through GARC, including non QoS agnostic flows (background / non real-time traffic).

The network exposes this functionality as part of the implementation through the messages:

Those messages are kept generic and are exchanged over the Northbound API (NBI) between GARC and the network - e.g. an OpenFlow Controller. No implementation of a NBI is available at the time this thesis was written, whereas an own REST implementation was developed as an extension of OpenFlow Controllers.

Each OpenFlow controller uses the passed arguments to create equivalent ONF conform OFP messages: `(OFPFC_ADD, OFPFC_MODIFY,OFPFC_MODIFY_STRICT, OFPFC_DELETE, OFPFC_DELETE_STRICT)` and transmits them to the respective network entities.

As depicted in Figure 5.3 the GUI lists data flow statistics and supports flow control management functionalities.

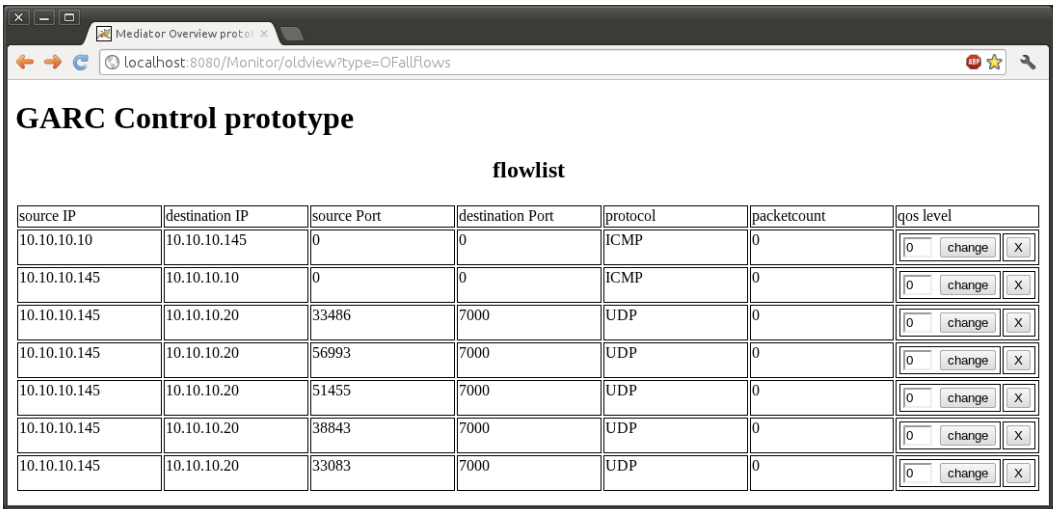

Figure 5.3: Browser-Based Flow Control Management Function

The virtualization of the TFT allows the identification of specific flows. A Java based Tomcat container has been selected for hosting and realizing the GUI. An external and reusable control and observation mechanism for GARC has been realized in the form of a GUI. Active QoS management on a per flow basis is achieved through active modifications of the flow priority in the field QoS level. Current packet-count and protocol enrich the information level further.

5.1.5 Real-Time Flow Display Implementation

The Real-Time Flow Display depicted in Figure 5.4 has been implemented to expose human-readable insides of the network data flows. All flows are presented as individual graphs identified over TFT using source and destination IP, port and protocol information.

The Java-Script JQuery project has been used for realization, because of its flexibility as well as the support for AJAX for a dynamic GUI.

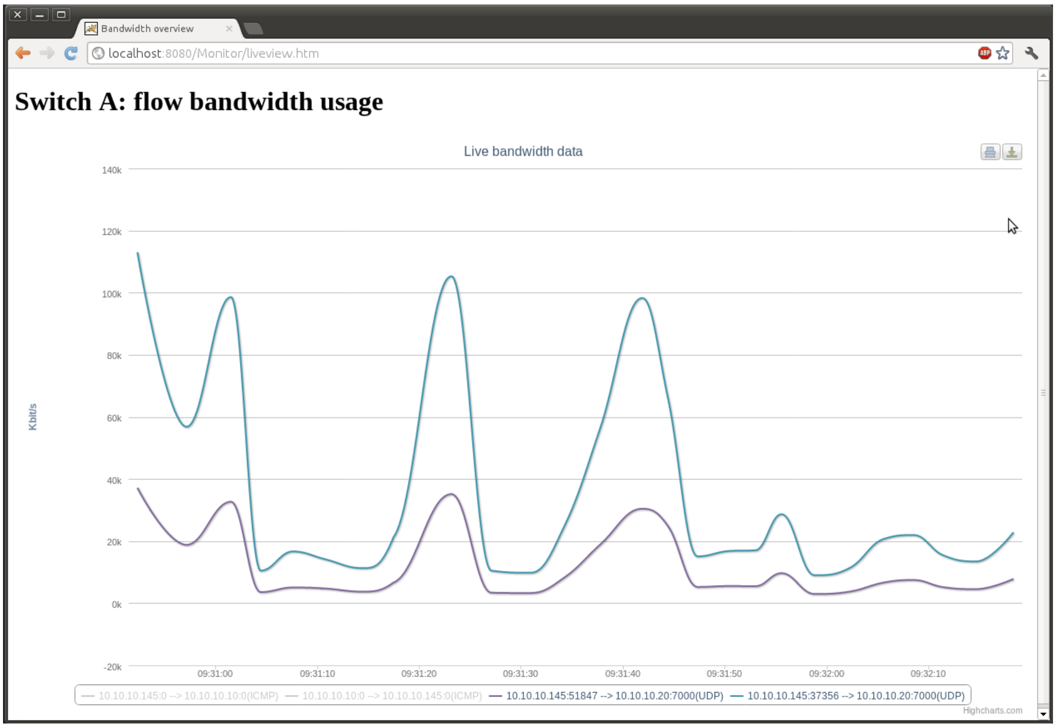

Figure 5.4: Browser-Based Real-Time Flow Display

5.2 Major Reference Points Implementation and Information Flows

This section outlines the software technical implementation of the three main reference points specified for GARC.

- End user devices: An application on the client side reports system statistics, packet loss ratio and user demands towards GARC.
- (3rd-party)-services or 3GPP Application Function (AF): An interface for service registration has been implemented over which services expose their control mechanisms and parameters towards GARC.
- Open and programmable networks: An abstraction layer has been implemented to provide a unified control interface exposing heterogeneous networks' control towards GARC.

The integration of three network technologies is outlined exemplarily, to show and validate the generic architectural concept. These are namely the 3GPP Evolved-Packet-Core and IP Multimedia Subsystem both representing a mobile core network, SDN OpenFlow representing network virtualization and finally Wireless LAN as a well established access network technology. Other interfaces to open networks are possible, but have not been considered in this phase of the prototype implementation.

5.2.1 GARC to UE and Service Reference Points Implementation

Two types of reference points are aggregated in this subsection. The implementation of the reference point towards the End user devices / UE is presented first, after outlining the interface towards (3rd-party)-services or 3GPP Application Function (AF).

The GARC to User reference point is located between GARC and an optional client software for service control. GARC is enabled to offer Quality of Service improvements to the user through this interface, by offering it directly through the service to the consumer, where the user can either accept or decline the offer.

GARC Initiated QoS Offer A JSON based proprietary protocol implementation for the message exchange has been implemented, which supports the following messages types:

- **Service started** is sent to GARC when the client starts using a specific service. The message contains the connection details to the application server, including the involved addresses, port numbers and protocols. Furthermore it includes the capabilities of the user.
- **QoS offer** is sent from GARC to the client. The message includes names of the current and offered new quality of service level. The message also includes a price for the offer and optionally a duration limit measured in time.
- **QoS offer reply** This message is sent from the client to GARC after the offer is either declined or accepted by the user. It contains a field indicating the user's choice.

For both the GARC to service and GARC to user reference points there is still an authentication step necessary in the concept that we also left out in our implementation. This interaction has been implemented with Unix console commands.

GStreamer Client Side An extensive State of the Art comparison of adaptive and controllable multimedia streaming approaches has been performed as outlined in C.1. None of the available solutions have been proven to be open, network-aware and adaptableenough for the realization of the GARC services. Therefore the development of an adaptive GStreamer-client and -server supporting various bit rates, frame rates and resolutions has been done as part of the thesis.

The gst-client and gst-server are initiated on a fixed particular predefined port.

The terminal (client side) signals device capabilities (screen resolution, supported network interfaces, IP address, list of active application and referring ports, etc.) towards GARC using the GARC-to-Device interface 4.6.1.

The network-aware gst-server communicates a list of QoS levels (pairs of upper- and lower-boundaries with max. bit rate, guaranteed bit rate) towards GARC using the GARC-to-network-interface 4.6.4.

Therefore, gst-server first signals its quality parameters (maximum and minimum supported bandwidth, available CODECs and the size of the steps measured in bit rate used to increase or decrease the total bit rate) to GARC.

A x264enc video encoder module of GStreamer has been implemented to support adaptive bit rate changes, but alters the source port after re-establishing the multimedia stream on the new bit rate level. In order to reduce signaling of bearer QoS level changes in addition to bearer modification events, a simpler way to keep the source and destination IP addresses and ports in a fixed stable state has been identified. Basically a split of the gst-server into a proxy having a fixed address and a streaming server instance has been implemented. The gst-server streams from various source ports to a fixed proxy, which forwards the flows with varying QoS parameters on a stable path between proxy and destination (gst-client). Each port change of the gst-server - caused through the QoS modification at the GStreamer streaming server - is handled transparently to client side, since the proxy remains on its fixed IP address and port.

GStreamer Server Side The GARC to service reference point is located between GARC and any network-aware application server. The gstr-server has been implemented as one realization of this reference point. Following our Cross Layer Optimization approach, this interface enables GARC to receive network resource reservations from applications, and also provides feedback to the applications, allowing them to adapt the service quality to the network's available resources continuously. Beforehand the network-aware GStreamer Server Side signals discrete operational level towards GARC. Those operational QoS level consists of a list of frame-rates, resolutions and bi-rates on which the service is able to operate. After receiving such service profile at GARC, GARC is able to adjust those operational QoS level according to the underlying network condition. This limited scope of requirements allowed this solution to rapidly implement a JSON based protocol that is easily extensible to other service domains.

The following messages are sent by the application server to GARC:

- **Service started** is sent when a new client requests a service. It contains the connection details to the client, the type of service and the adjustable parameters as well as their initial values and boundaries for different quality levels.

- **Service adjusted** is sent as confirmation when a service is adjusted after a request from GARC.

- **Service terminated** is sent to inform GARC that a connection to a client has terminated.

GARC on the other hand only sends **adjust service** messages to the application. These either let the application switch to a higher or lower quality class or specifically adjust one or multiple quality parameters.

The following implementations have been enacted for realizing the adaptive gst-server.

The input source is designed to be flexible to stream either a test picture, a static pre-recorded local file or real-time High Definition live web cam stream. The x264enc pipeline element of GStreamer supports bit rate modifications dynamically but each change causes a re-initialization of the RTP streaming. This re-initialization is followed by a re-establishment of the RTP streaming, which changes the source port and re-initializes the RTP packet number randomly. Each data stream is correlated with a logical bearer within a 3GPP network according to the standard. Changes in the data stream affect the bearer in turn.

A proxy is introduced into the streaming architecture, in order to avoid the adaptation of the bearer after each bit rate change. An UDP proxy with a fixed port and IP address serves as counterpart to the server and forwards each packet to the client in the end.

This pipeline first accesses the USB video device over v4l2src and encodes the resulting raw data stream in a flexible resolution, bit rate and color space. Finally the data stream is divided into chunks of data which are encapsulated into RTP packets and are forwarded to the proxy.

5.2.2 Network Management Functions Implementation

After depicting the key design decisions on the network adapter layer in the previous chapter 4 we now present the most relevant implementation specific details. The software technical realization consists of 3GPP EPC and IMS functions, as well as SDN OpenFlow Controller, Switch and Protocol and 802.11e WiFi.

Software Defined Network / OpenFlow Adapter The GARC to SDN reference point is located between GARC and the SDN controllers and is responsible for enabling two major functions of GARC:

Network monitoring: The main function is the continuous analysis of measurements that are read from the network. GARC aggregates the derived information in order to maintain a detailed view of the network topology, real-time link information and the states they are in. This kind of real-time information is used to provide a decision basis for the traffic engineering and a negotiation basis for attached services. Furthermore it provides input for real-time graphical statics for the GUI.

Traffic Engineering and Network Management: The control of traffic on a per flow basis in the network can have different specific and general goals, e.g. maximum capacity utilization, minimal delay, quality of service or low energy consumption. Real-time flow information and post processing of the monitored data are used for data analytics, which triggers the Network Management and Traffic Engineering module in GARC.

This scope of operation is equivalent to a northbound API in the SDN stack, in that it enables an overlying application to interact with the controller, which in turn interacts with the underlying networking entities. The Northbound Interface (NBI) for OpenFlow is not yet standardized by ONF and to date each vendor still implements its own protocol. The difficulty lies in the multitude of implementation specific network controllers' northbound APIs. Since GARC has been designed to follow a 'generic' approach, working with the Open Source network controllers NOX, POX and the FOKUS OpenFlow version 1.4.0 implementation on Wharf, it has been designed and implemented with a proprietary JSON-RPC northbound API.

Wharf as a Platform for Developments Wharf is a C-based framework developed at Fraunhofer FOKUS and has been used as a platform to develop the following functionalities. It is considered to be a flexible and powerful prototyping platform for NGN components and designed to support multiple protocols and applications in the telecommunication domain. Wharf was successfully developed as part of the SIP Express Router project by Fraunhofer Institute FOKUS, which led to the famous OpenIMSCore project [166].

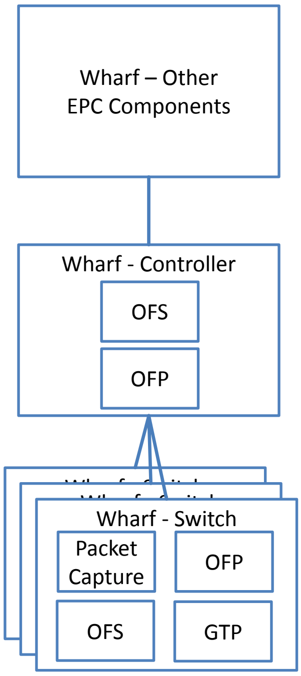

Figure 5.5: Wharf Platform for Software Defined Telecommunication Networks

The Wharf platform has further evolved from that point on through continuous enhancements and is now reused as part of the OpenEPC project [167] as a prototyping platform for Next Generation Networks. Wharf is a module-based framework supporting different independent modules. Each Wharf module is a library dedicated to a certain functionality (e.g. protocol stacks, interfaces, I/O, etc.). Wharf provides the platform for modules to register/unregister themselves and communicate with each other using standardized interfaces. Wharf loads and manages modules dynamically according to the configuration files given by a user. In our prototype, the Software Defined Telecommunication Switch, Controller and Protocol are implemented as separated Wharf modules. To handle the interaction between controller and switch, an OpenFlow Protocol module (OFP) was developed to provide the basic data structures and message schemes defined in [13].

Figure 5.5 depicts a general view of the EPC prototype running on Wharf. Instantiations of Wharf can be realized in a very flexible way. Several Wharf instances can be hosted distributed on different machines, with each one containing an EPC component. The mapping of Wharf instances and modules/components can be 1:1 or 1:N. Therefore flexibility is introduced when deploying the components individually or combined.

The two highlighted components in the picture provide a zoomed out view of the controller and switch. In each switch instance, the OFS acts as a GW-U component by using the functions provided by other Wharf modules such as packet capture and GTP processing. The connections between modules in the figure indicate the internal programming dependencies. And on the controller side, the GW-C component is implemented as an application using the local API provided by OFC. The OFP module in both instances forms the OpenFlow channel, connecting the controller and switches.

The next two paragraphs outline the development of the OFC, OFS and OFP for enabling Cross Layer Optimization for pure OpenFlow domains and Software Defined Telecommunication Networks.

OpenFlow Controller (OFC) The OFC module in Wharf implements functions of the OpenFlow Controller and is further presented in [164, 148]. It is developed based on the architecture introduced in 4. The OpenFlow channel between OF Switch and OF Controller runs over plain TCP, but could be extended to use TLS for securing the connection. OpenFlow messages will be encoded into bytes and sent over the socket stream. Functions exported by the OFC module form the local northbound API of the controller. Other Wharf modules can gain access to controller functions by using this API. To expose the API also through the network, JSON-RPC is selected to be the carrier protocol. JSON-RPC is a lightweight remote procedure call protocol [168]. It uses JSON as data format, which is known to have high expressiveness and is widely used in lots of network projects. JSON-RPC can be implemented by either TCP, UDP, HTTP or any other transporting protocols. This design gives it maximum flexibility and extensibility. The OFC module maintains a JSON-RPC API server. Remote applications or service processes supporting JSON-RPC can access the API functions by simply making RPC requests.

OpenFlow Switch (OFS) The OFS module in Wharf implements basic parts of the OpenFlow Switch and is further presented in [164, 147]. OFS uses other modules like the OFP module described in section 4, the packet capturing module, the GTP module and other modules providing basic functionality for interacting with the switch. The current implementation allows for the definition of several interfaces with several different IP addresses. Internally, one process for each interface is taking care of sending and receiving packets via a raw socket. During the processing of the packet in the pipeline it is necessary to decide whether to decouple the pipeline processing from the current process or to finish it within the initial process. In the case of GTP/GRE processing, it makes sense to split this packet processing from the initial process. As long as the processing task is small enough to keep the forwarding speed at an adequate level, it is not necessary to split it. The tasks in the queue will then be executed by some worker processes that are independent from the capturing mechanism. The worker/task/scheduler concept is part of the core Wharf functionality. The pipeline processing includes the necessary steps to match the packet header with the flow table entries, execute actions on the packets and handle instructions upon packet matches. Current flow entry match lookup is implemented as a linear list.

Traffic Detection Function (TDF) and Deep Packet Inspection (DPI) Network-awareness has also been achieved through interfacing prototypes of TDF and DPI over the Sd reference point. Limited traffic detection functions (TDF/DPI) have been implemented as services residing on the data path to identify the type and state of a connection.

Examples are TCP SYN/ACK and FIN messages identifying a connection's establishment and termination.

Other examples include shallow packet inspection for identifying real time streams using RTP by analyzing the UDP packet header.

The information gathered on the data path for each Traffic Flow Template is signaled on towards GARC.

Diameter Reference Point To evaluate the integration of the Cross Layer Optimization approach into the mobile networking domain, the GARC functionality has been implemented into existing 3GPP architectures. Therefore the IP Multimedia Subsystem (IMS) architecture for the control and enhancement of multimedia services has been selected as one of two Proof of Concept (PoC) implementations. GARC has been implemented into the 3GPP Evolved Packet Core for the control and enhancement of All-IP services as part of a second PoC.

An existing Diameter protocol stack as part of Wharf has been used as a basis for realizing the interaction between GARC and 3GPP network elements. New 3GPP conform protocol messages have been implemented to support Gx, Gxx and Sp messages as described in detail below.

For this we used the FOKUS open source OpenIMSCore and extended it with a PCRF component from the FOKUS 3GPP Evolved Packet Core implementation OpenEPC. The goal here was to have a GARC controlled SDN as access network and provide QoS enforcement for IMS- as well as non-IMS multimedia streaming applications and services. Bandwidth and priority requirements from IMS applications (VoIP, VoD) are processed by the PCRF and enforced by GARC instead of a PCEF component. Non IMS applications communicate their requirements via the GARC to a service reference point and with access to HSS datasets. GARC enforces these requirements inside the limits of the user's subscription coverage. Instead of extending the existing 3GPP telecommunication control plane components with additional interfaces, existing 3GPP reference points have been realized and implemented in GARC. Backwards compatibility to other IMS or EPC solutions has been achieved through this approach.

The Gx Reference Point is located between PCRF and GARC (located between PCRF and PCEF in the 3GPP architecture). For our showcase scenario of a video stream from a SIP client, we decided that it is sufficient to support the Gx messages RAR and RAA, since charging control was irrelevant for our experiments at this stage of the prototype. The RAR messages coming from the PCRF include information about the QCI level and bandwidth requirements of a service, while the RAA messages to the PCRF signal the success or failure of an enforcement.

The Sh Reference Point between GARC and the HSS is a 3GPP specified interface for querying and updating user information. The main intent for implementing this interface is to access user profile information for further decision processes in GARC about determining the QoS level. GARC therefore acts as an Application Server (AS), which is allowed to request user data via the sh-pull message. Unfortunately user-allocated IP addresses are not stored in the HSS. An extension of the user database by adding the user's IP address(es) has been implemented.

GARC to WiFi 802.11e Reference Point The aim was to realize a generic control mechanism for QoS in WiFi 802.11e. Therefore a proxy module has been developed, which can accept commands to set QoS, validate these, and execute them in the local environment. The development process consisted of two different approaches: daemon and TCP server. In the beginning, a daemon-based proxy was implemented, which responded to command line arguments. This also determined our choice of a programming language - a scripting language for simplicity that works well on Linux and is not very complex has been targeted. Using Python, a daemon module was implemented that can respond to three commands: "start", "stop", "qos". The last approach was the central one of the implementation and is depicted in 5.6. The Python daemon expected a number of parameters (IP address, ports, QoS level) in the connection to be prioritized by GARC.

Finally a Linux shell command was executed, which invoked iptables to create

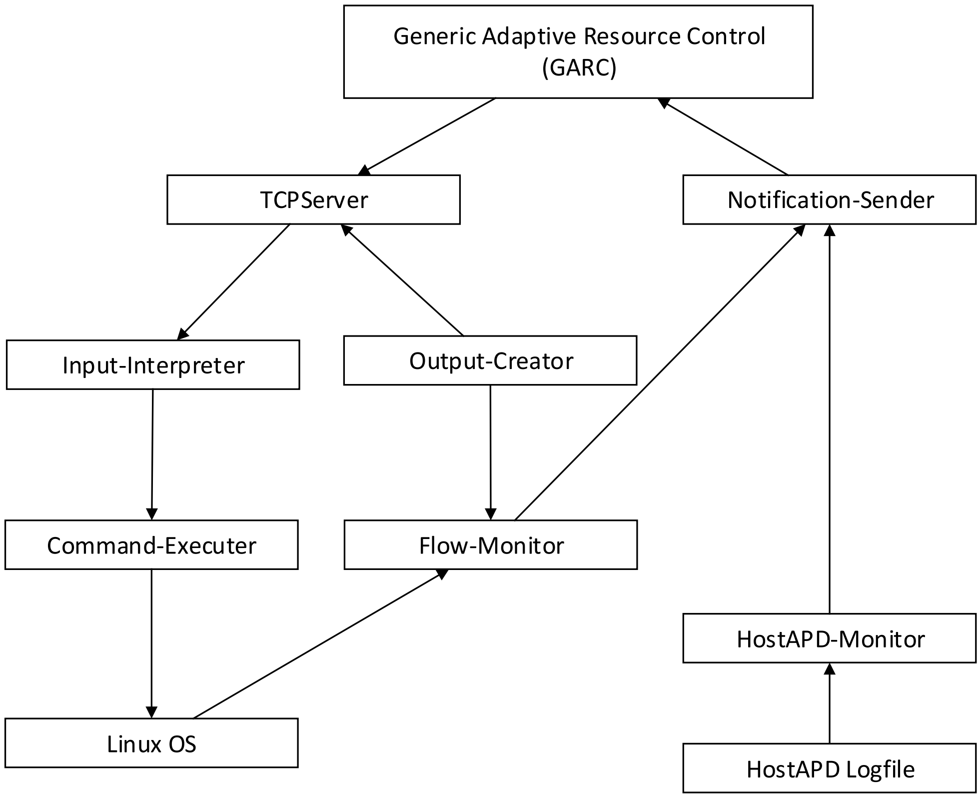

Figure 5.6: GARC Adapter for WiFi 802.11e QoS Control and Management

the packet-managing rule. To do this, the underlying structure of the implementation from a daemon to a TCP server has been changed. An own handle method was implemented in order to take over control of the events. The only downside of this approach is that there is no possibility to form long-lived TCP connections. The new server supported the same QoS control as the daemon before.

Finally, the result of this implementation was integrated and validated by implementing a sample TCP client that could connect to the wireless access point and issue QoS commands. The setup included two laptops, one of which was a WLAN AP and runs the proxy module. AThe setup is evaluated in the following section 6.4.3. Two flows were created using IPERF and one of these was given a higher QoS of service.

The implementation consisted of two parts basically: a WifiInterface that acts as a TCP client and connects to the proxy server, and a NotificationReceiver that is the TCP server that listens for PUSH notifications. The WifiInterface keeps track of a number of (remote) APs that are running the proxy. The interface can receive commands from GARC that contain a single keyword and an AP ID, at which point the interface connects to the proxy instance on the relevant AP and issues the desired command. It waits for an answer, parses it into a GARC-compliant format and sends it a framework. The Notification Sender works in a similar fashion, but skips the first step and instead just reports proxy messages to GARC. These functions are part of the implementation and include a connection towards GARC.

QoS Module for Evolved Packet Core As part of this thesis, a QoS module has been designed and implemented in Wharf for the Evolved Packet Core OpenEPC.

Several schedulers for QoS support have been analyzed and compared, as outlined in C.2 in the Annex. The concept of integrating the scheduling mechanisms into the 3GPP EPC was presented in 4.6.4.

This paragraph highlights the most relevant implementation of a Token Bucket algorithm that was realized in the QoS module.

The token bucket is a counter that has two parameters: the token rate and the burst size. It simulates a bucket with tokens coming in at a certain token rate, and it can contain no more tokens than its burst size. When a new packet is accounted for, the number of tokens equal to the size of the packet is taken from the bucket. If there are not enough tokens, the packet conforms to the rate limit and is passed further along, otherwise the non-compliant packets should be queued or dropped. Therefore, the burst size is the maximum number of bytes that can be sent at once with the maximum physical rate of the channel. This parameter should be greater than the maximum allowed packet size. The token bucket can also predict when it will be possible to send the next data packet.

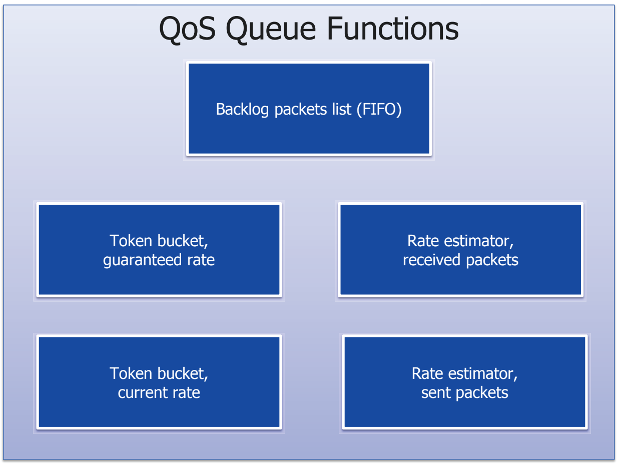

Figure 5.7: Queue Management for QoS Support within OpenEPC

The estimators update the estimation of the byte rate with every packet using the exponential weighted moving average (EWMA) formula $r_n = (1 - w(\Delta t))r_{n-1} + w(\Delta t)(x_n/\Delta t)$. Here r_n is a byte rate estimate after the n-th packet, x_n is the size of the n-th packet, Δt is the time interval since the previous packet. $w(\Delta t)$ is a weight that depends on Δt: the recent events have more weight. $w(\Delta t) = 1 - e^{(-\frac{\Delta t}{\mu})}$ where

μ is a time constant that represents the sensitivity of the estimator to temporal changes. For a special case $\Delta t \approx 0$ $r_n = r_{n-1} + x_n/\mu$, it can also be used for the first packet initialization.

After a new packet enters the QoS module, it is assigned to one of the queues and added to the end of the queue, and the counters of the incoming estimator are updated. If the queue is full, the packet is dropped. Then all non-empty queues are checked in the order of priority, and if a queue can send, the topmost packets of the queue are passed to the routing module in Wharf using a callback and are accounted for in the outgoing estimator. After the packets are sent, the list of the queues is rearranged: empty queues are removed, and the timestamps when the queues can send are recalculated, if needed. The nearest time stamp is updated, and the timer is notified. The timer process reads the time stamp and waits until it exceeds. If the timer timeout ends successfully, the queues check is performed again (without new packets), and the new timer time stamp is set.

Software Defined Network Monitoring This function is covered as part of the Northbound Interface and GARC to Network Interface through a specified set of messages that addresses different aspects of switches and the whole networks state:

Request flow statistics.

Request port statistics.

Request queue statistics.

Request topology.

Part of the OpenFlow protocol standard allows the retrieval of flow-, port- and queue- statistics that can be requested from supporting switches by the controller. For our northbound API implementation the network controller requests these statistics from all switches and all ports and sends them bundled to GARC, where they are stored and updated in order to maintain a complete view of the networks' state. Network topology discovery is not part of the OpenFlow standard but can be achieved by the controller through a combination of Link Layer Discovery Protocol (LLDP) for the switches and tracking of packet origins for the hosts.

5.3 Summary

This section presents and summarizes all parts of the architecture, functional elements and reference points specified in section 4, which have been implemented in the scope of this thesis. An extensive list of Open Source software tools relevant for the realization of this software project is provided in the Annex C.3. As a main contribution of this section, software technical aspects for realizing the high level functions of GARC are listed and its implementation details are discussed in 5.1. The three main reference points of GARC towards the UE (5.2.1), application and services (5.2.1) and network (5.2.2) are presented and discussed in its implementation.

The following Chapter 6 on *Validation* reviews the aspects of the *Implementation* presented in this Chapter 5 against the *Requirements* initially presented in Chapter 3.

Chapter 6

Validation and Evaluation

Chapter 6 *Validation and Evaluation* compares the requirements identified in Chapter 3 against the concept described in Chapter 4 and the implementation highlighted in Chapter 5.

After first presenting the concept, followed by the implementation, this section validates the previous sections through extensive test scenarios and discusses the results. [1]

The validation chapter itself is split into the following main parts:

- Proof of Concepts (PoC) implementation validation - GARC has been validated against 3GPP (IMS, EPC/LTE) and non-3GPP (WLAN, SDN) networks as well as applications (Skype, adaptive video streaming, SIP based IMS applications). Parts of GARC have been integrated in Fraunhofer FOKUS toolkits and validated as part of larger demonstrations. Concepts of GARC have been adapted in ICT proposals and emerged as ICT projects.
- Experimental validation - Specific use case scenarios defined in Chapter 4 have been validated.
- Observational methods and validation - Concepts, message flow of sequence diagrams and the correct behavior of GARC compared to the requirements and specification have been validated.

6.1 Requirement Analysis Evaluation

Chapter 3 collects and summarizes the requirements affecting this work. This section analyzes the previously defined requirements against the specified and developed GARC system and therefore validates the correctness of the approach.

Table 6.1 maps the key requirements of the previous chapter against the supported features of GARC. Not all requirements identified in Chapter 3 have been realized by GARC. A trade off between a large number of requirements and a reasonable scope of the thesis has been found, by selecting only the set of key requirements presented here. Their selection and related functionality within GARC is motivated and explained in the following.

Openness and expandability have been achieved by introducing layers in GARC. The core logic of GARC has been abstracted through upper and lower layers. Those layers allow the introduction of new networks and services by adding another adapter to GARC.

Network, service and end user customer interactions have been achieved through the Cross Layer interaction model as explained in Sections 4.5.3, 4.5.4 and 4.5.5.

The model extends the scope for adjustment and control of resources from a single domain (e.g. 3GPP EPC) to multi domains. Those domains include access network, core network, data center/service plane and end user customer devices.

Self adaptation and Flexibility make up one aspect of self organizing systems, and consist of a chain of cause-and-effect that forms a circuit or feedback loop.

[1] Results of this chapter have been published in [37, 38, 39, 40, 41, 144, 42, 145, 146, 147, 148]

Requirements	Evaluation of GARC
End User Interaction	User demanded resource requests are supported
Network Aware Services	Supported
Service Aware Networking	Supported
Dynamic Traffic Engineering	Algorithm for dynamic Traffic Engineering supported
Adaptive Network Management	Algorithm for adaptive Network Management supported
Cost Efficiency	GARC includes approaches for reducing OPEX and CAPEX for the network operators and service providers
Heterogeneous Network Support	Yes
Context Information	Context: location, positioning, UE profile, coverage maps
Scalability	Aspects included in the concept, but not included in the implementation
Usability	Simplified UE interaction model
Openness and Expandability	Network adapter layer, standard Diameter support, optional network element
Adaptability	Adaptable to real time situations and states of applications and networks
Extensibility	Highly adaptable for further extensions towards applications and networks
Self Adaptation, Flexibility, Elasticity	Adaptive network design, Traffic engineering
Device Capabilities	Device capabilities are included in the concept in the policy decision process
Service Interaction	Northbound API, PCRF Diameter reference point support
Network Interaction	Southbound API, Open network APIs
End User Interaction	User demanded QoS, Enhanced ANDSF features
Policy Decision Point	PCRF support
Policy Enforcement Point	3GPP policy enforcement mechanism support
Reporting Functionality	Subscription and notifications are supported
External Control Interface	An external GUI is exposed for management and control
3rd Party Support	External network-aware and non network-aware services and applications are supported
Roaming Support	Available

Table 6.1: Mapping Requirements against GARC Features

This feature allows changes of system configuration within a predefined range of parameters, in order to react appropriately to internal or external changes in the system environment.

Elasticity has been realized through the enabling of demand driven service map and topology adaptations and modifications. Resources in the service, network and end user device domain are elastically adjusted as explained in section 4.5. System efficiency and resource savings in terms of lower CAPEX and OPEX have been achieved.

Usability for the end user customer of GARC is simplified due to the reduced interaction and usage as explained in section 4.6.1. A common understanding of the End User for the interaction is required, but no technological details are needed. The interaction between the end user and the network - respectively GARC - can proceed in two ways: first, through an additional application on the user device and second though a web front end of GARC. Both communication paths are designed to take secure channels. An application on the device maps priorities to applications as meta information and signals that meta information to GARC. This meta information includes application destination IP addresses (e.g. company VPN domains), dedicated ports (e.g. local static Skype port) or other well known services. After the initial authentication of the end user customer, the user is able to prioritize installed or active applications on its device dynamically. The prioritization can either be done through an ordered list of applications which is modified via drag and drop, or through the manual assignment of values indicating low, medium or high priority classes to applications. A webfrontend allows static configuration of common or individual configurations with the same features as the application.

6.2 ICT Project Validation and Dissemination

This section summarizes the contributions of the thesis' ideas, concepts and implementations as part of international ICT projects. The below mentioned projects are ordered chronologically.

6.2.1 BMBF G-Lab DEEP Project

The BMBF funded G-Lab-DEEP project [22] focused on 'Deepening and Extending G-Lab for Cross Layer Composition and Security (G-Lab Deep)'. Novel Cross Layer approaches applicable in the current Internet, Next-Generation-Networks and Future Internet architectures have been developed as part of the G-Lab DEEP project. Current State of the Art service control and Cross Layer approaches have been analyzed, identified and compared within the scope of G-Lab DEEP.

One major outcome of G-Lab DEEP and the foundation for this thesis is the mediator Cross Layer [91, 92, 90, 37, 38, 40] concept, implementation and validation in addition to security and federation related work.

6.2.2 Fraunhofer FOKUS Broker

The Fraunhofer FOKUS Broker supports policy-based service access, orchestration and composition and is part of the FOKUS OPEN SOA TELCO PLAYGROUND for Open Telecommunications Testbed based on SOA principles. The broker concept supports telecommunication service management on the application layer and is independent of the underlying transport network technology.

In order to provide flexible network-aware application based QoS control, the FOKUS Broker implements the 3GPP Rx Diameter reference point.

As part of the G-Lab DEEP project, Cross Layer Optimization has been implemented in the FOKUS Broker as described in the following.

A first prototype uses the Fraunhofer FOKUS broker because of the enriched functionality already provided by this component. The FOKUS Broker represents the main entity which ensures the service management in a service delivery platform. It offers a service registry for announced services, an environment for the execution of services and an access control and personalization entity.

A schematic overview is depicted in Figure 6.1 and the Cross Layer interaction is highlighted as part of the GARC concept.

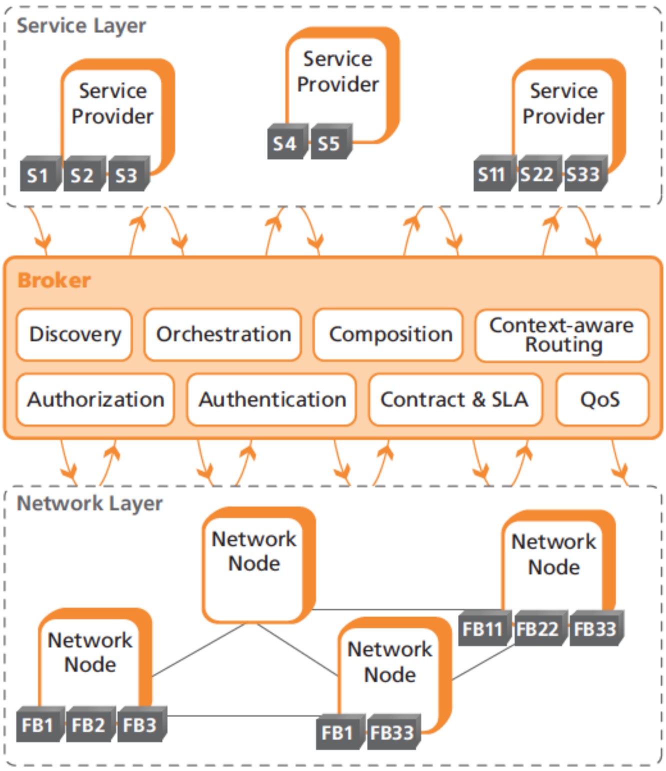

Figure 6.1: Cross Layer Optimized within Fraunhofer FOKUS

A policy engine extends the functionality of the service broker with access control and personalization. The policy engine evaluates operator given policies, which result in a specific behavior through enforcing the rules with the framework. The policies have different priorities based on the identities which defined them. Thus the highest priority belongs to the policies defined by the system, followed by the policies defined by the service providers and later by the service customer. Policies are identified as a logical set of rules in which each rule consists of conditions and actions. During the evaluation, specific policies are selected (based on the service name, operation name, originator of the invocation respective to the target of the invocation) and their conditions are evaluated against specific parameters (e.g. platform parameter, service parameter etc).

The scenario realized through the broker highlights QoS on a voice data connection, which differentiates prioritized emergency calls from not prioritized normal voice calls. In case an emergency call is requested in the intent statement by the UE, the policy engine activates a rule, which includes the service level requirement prioritization in the composition workflow created by the composition engine. Those rules are enforced in the network.

The first stage of the Cross Layer mediator passes requirements from the service down to the network layer without negotiating and optimizing the connection parameters because of simplicity. Therefore flow information is extracted by the mediator and the appropriate functional composition framework is selected afterwards, which appropriately enforces the requirements.

6.2.3 FP7 ICT IP FISTAR Project

The FP7 IP 'Future Internet Social and Technological Alignment Research' (FISTAR) runs in the activity Objective 1.8 Use Case scenarios and early trials. The GARC functionality is explicitly mentioned in the Description-of-Work (DoW) and will be developed further within the scope of this project.

FI-STAR will establish early trials in the health care domain building on Future Internet (FI) technology leveraging on the outcomes of FI-PPP Phase 1. It will become self-sufficient after the end of the project and will continue on a sustainable business model with several partners. In order to meet the requirements of a global health industry FI-STAR will use a fundamentally different, 'reverse' cloud approach; it will bring the software to the data, rather than bringing the data to the software. FI-STAR will create a robust framework based on the 'software to data' paradigm. A sustainable value chain following the life cycle of the Generic Enablers (GEs) will enable FI-STAR to grow beyond the lifetime of the project.

FI-STAR will build a vertical community in order to create a sustainable ecosystem for all user groups in the global health care and adjacent markets based on FI-PPP specifications. FI-STAR will deploy and execute 7 early trials across Europe, serving more than 4 million people. Through the trials FI-STAR will validate the FI-PPP core platform concept by using GEs to build its framework and will introduce ultra-light interactive applications for user functionality. It will pro-actively engage with the FI-PPP to propose specifications and standards. FI-STAR will use

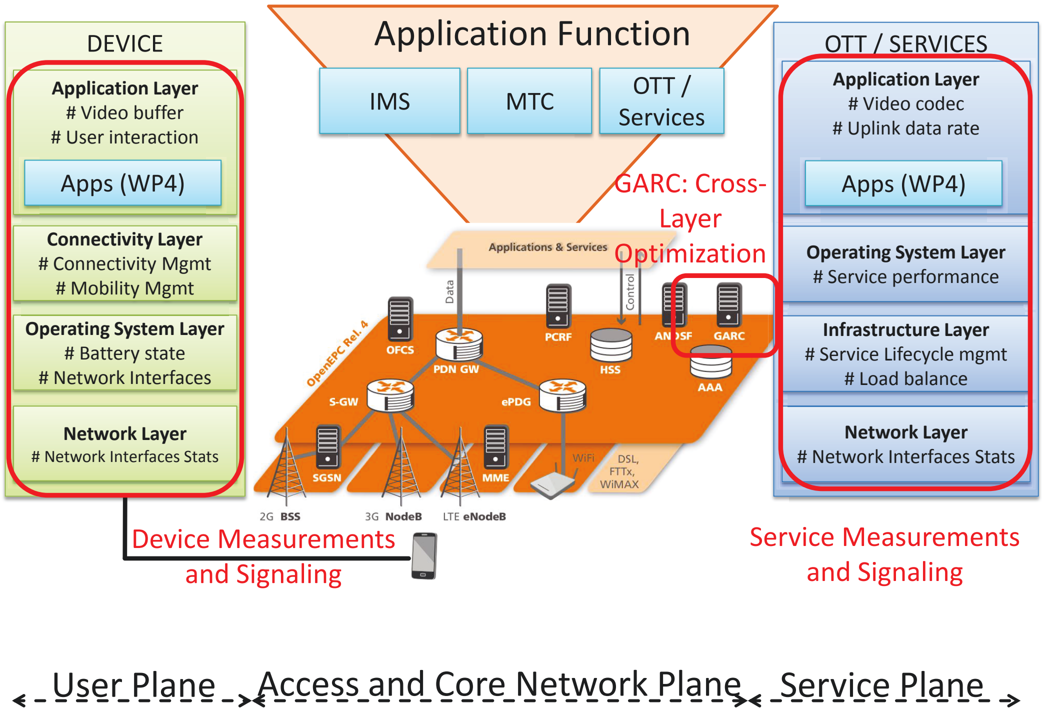

Figure 6.2: Mapping GARC Functionalities on FISTAR Use Case 8 Architecture

the latest digital media technology for community building and will pro actively prepare for Phase 3 through targeted elicitation of new partners using open calls.

Finally, FI-STAR will collaborate with other FI-PPP projects, through the mechanisms in place, by actively interacting with all necessary bodies. FI-STAR is a unique opportunity for implementing Future Internet Private-Public Partnership in the health care domain, by offering to the community standardized and certified software including a safe, secure and resilient platform, taking advantage of all Cloud Computing benefits and guaranteeing the protection of sensitive and personal data traveling in public Clouds.

GARC will be deployed in seven early use case trials to especially enhance 3GPP telecommunication networks and Software-Defined-Networks (SDN). The flexible control mechanisms will enhance data transport between cloud data centers and hospital infrastructures over fixed and mobile networks. Work package two (WP2) and three (WP3) will explicitly extend the FI WARE platform for flexible QoS enhancements. User demanded QoS requests will be supported by dedicated novel applications that are specified in work package four (WP4).

Moreover a Use Case 8 has been defined for applying the GARC concept in the scope of an eHealth environment. The combination of Machine Type Communication (MTC) on top of telecommunication infrastructures such as the EPC has been targeted. The enforcement of QoS for dedicated services for critical infrastructures (e.g. in a hospital/clinic environments) has been identified and realized as a prototypical proof of concept implementation.

Figure 6.2 depicts the influence of GARC on the FISTAR system architecture. Applications running in the service domain are enabled to signal QoS requirements into the network. Heterogeneous access and core networks are supported through the architecture. FISTAR applications for remote patient monitoring (blood pressure, hard beat rate and glucose measurements as well as movement tracking) are supported. The concepts of GARC are enabling application-aware networking, in which FISTAR apps developed in WP4 are signaling application layer requirements into the network. The GARC component - as an optional extension in the telecommunication network - translates generic QoS requirements into specific network technology related requirements. In order to meet the QoS requirements demanded by the application, mobility, connectivity and resource management can be controlled and managed accordingly.

6.2.4 Fraunhofer FOKUS OpenEPC Project

The OpenEPC project [167] of Fraunhofer FOKUS and TU Berlin is a prototype implementation of the 3GPP Evolved Packet Core (EPC). It provides a testbed foundation and enables academic and industry researchers and engineers around the world to perform fast prototyping with the capabilities of the Evolved Packet Core. OpenEPC Rel. 5, the current version available, includes all the components of the 3GPP architecture together with interfaces for supporting various access technologies and service platforms.

As part of this thesis, novel concepts and functionalities have been implemented in order to support service control functionalities.

UE initiated QoS requests Concepts, implementations and validations have been demonstrated [169, 92] and published [38, 91, 37].

Implemented as an optional component of the 3GPP EPC control plane, GARC has been introduced as new feature of OpenEPC Rel.5 successfully.

OpenFlow support in OpenEPC Rel. 5 The 3GPP standard envisioned the split of signaling and control planes. Two types of gateways (SGW, PGW) handle Use-data plane traffic and control functions (MME, PCRF) handle the control plane traffic in turn. Logic is still included in the gateways, since IP address allocation, charging, traffic control for up- and down-link traffic, routing and gating is part of the gateways.

OpenFlow protocol support has been integrated into OpenEPC as part of Rel.5 in addition to other functional enhancements and published under [164].

OpenFlow support for OpenEPC in Rel.5 now enables the User-data and Control plane split as depicted in Figure 6.3 of the 3GPP EPC gateways using latest OpenFlow standards in version 1.4.0. This includes a functional split of the existing

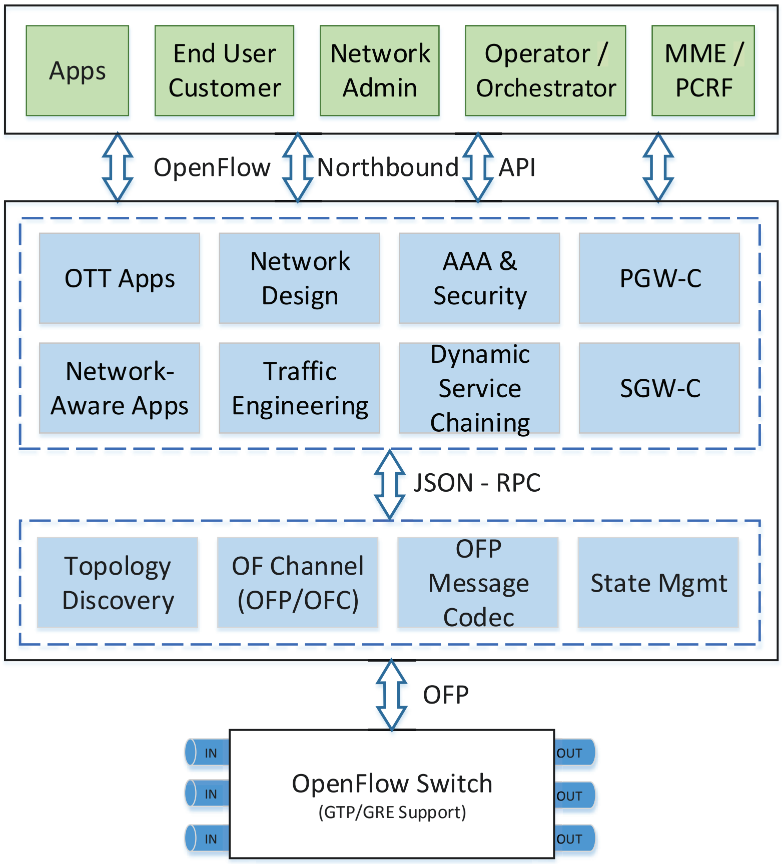

Figure 6.3: OpenFlow Support for (Open-)EPC

gateways in the infrastructure together with the integration of a new control interface. While based on OpenFlow protocol v1.4.0, the implementation also features new concepts, as required to provide the full EPC functionality while harnessing the full upcoming power of OpenFlow switches.

Goals that have been achieved due to the application of the SDN concept and the Cross Layer concept on the EPC architecture are, in summary:

- Flexibility on the data plane is introduced through the split of User-data Plane and Control Plane of the 3GPP EPC gateways (SGW, PGW) each into a pairwise control (C) and User (U) plane part.
- The OpenFlow protocol is used for communication between PGW-C/PGW-U and SGW-C/SGW-U.
- Flexible and distributed deployment of Control Plane components of individual functional network elements or combined functional elements of EPC in the NFV direction, followed more extensively by the OpenSDNCore [170] and Open5GCore [171] projects.

- Full compatibility between the OpenFlow-enabled-OpenEPC and existing EPC products and deployments.
- JSON-RPC Northbound Interface (NBI) for OpenFlow controller extensions, enabling network-aware services and Core Network enhancements for service-awareness for networks through Cross Layer signaling as described in subsection 5.2.2.
- Flexible Traffic Management including Adaptive Flow Placement and Elastic Network Design as described in subsection 4.5.3.
- Enabling concepts for fine granularity and per Service Data Flow, on-demand Quality of Service control 4.5.3.
- Elastic data path steering.

6.2.5 Fraunhofer FOKUS OpenSDNCore and Open5GCore Project

Parts of the thesis' concepts and results have been taken on by two other Fraunhofer FOKUS projects in addition to the OpenEPC Rel.5, which are namely OpenSDNCore [170] (The Service Enabling Platform for the NFV/SDN World) and Open5GCore [171] (The Next Mobile Core Network Testbed Platform).

OpenSDNCore OpenSDNCore itself is a practical implementation of the future network evolution paradigms, realizing Network Functions Virtualization (NFV) and Software Defined Network (SDN) concepts, providing early prototyping of a service enabling platform on top of common infrastructure components.

The generic OpenFlow Controller adapter layer and the GUI of GARC have been included in the OpenSDNCore project. In addition, the Cross Layer concepts of GARC have been applied to Network Functional Placement and Service Chaining. QoS requirements from application plane will be signaled towards the network plane.

The most important features and functions are:

- ETSI NFV MANO aligned Orchestrator integrated with OpenStack enabling the dynamic deployment and run-time management of virtual network functions.
- ONF OpenFlow 1.4 aligned Switch and Controller extended to support telco specific features.
- A set of best practices virtual network functions and their afferent adapters based on SDN components, OpenEPC and OpenIMSCore.

Open5GCore The Fraunhofer FOKUS Open5GCore is a theoretical specification and its practical implementation of the evolution of the mobile operator core network towards the integration of novel radio technologies beyond LTE and LTE-A.

Open5GCore aims at providing a first prototypical view of the core network handling the requirements of mobile subscribers and services, enabling the research and the hands-on proof-of concept before standardization activities.

Summary Both projects share the same basic concepts of SDN on the data path and Cross Layer concepts with switches, controllers and applications. Cross Layer Optimization plays an important role, since new requirements such as low delay (a few ms delay for local operations), high data throughput and a higher level of flexibility are targeted.

Both toolkits enable academia and industry research in the areas of SDN, NFV and telco, which share Cross Layer Optimization aspects of this thesis.

6.2.6 FP7 ICT IP MobileCloud-Networking Project

The FP7 IP MobileCloud-Networks (MCN) [24] converges the two domains of cloud and telecommunication to enable a cloudified telecommunication system. Key advantages of the cloud domain such as scalability and elasticity are applied to telecommunication network functions in order to deliver those as-a-service.

The OpenEPC is part of MCN and serves as one key building block for the project, on top of which new cloud functions are added.

The two concepts of SDN and NFV play an important role for MCN and are applied to the OpenEPC, too

Parts of the developments for GARC such as the OpenFlow extension of OpenEPC and the RESTful NBI are reused in MCN for configuration, provisioning and management of the mobile core data plane. The Cross Layer approach is adapted through the programmability of the data plane from the application.

6.2.7 FP7 ICT STREP NUBOMEDIA Project

The FP7 STREP project NUBOMEDIA [172] has been defined as an elastic Platform as-a-Service (PaaS) cloud for interactive social multimedia.

NUBOMEDIA aims to be the first cloud platform specifically designed for hosting interactive multimedia services. Its architecture is based on media pipelines: chains of elements providing media capabilities such as encryption, transcoding, augmented reality or video content analysis. These chains allow the building of arbitrarily complex media processing for applications. As a unique feature, from the point of view of the pipelines, the NUBOMEDIA cloud infrastructure behaves as a single virtual super-computer encompassing all the available resources of the underlying physical network. Thanks to this, NUBOMEDIA applications can elastically scale and adapt to the required load, preserving Quality of Service (QoS) and Service Level Agreement (SLA) guarantees.

NUBOMEDIA follows the mission to democratize interactive multimedia communication services by making their creation, deployment and mass-scale exploitation a cheap, rapid and effortless process. To achieve this, the NUBOMEDIA consortium uses a strategy composed of two axes. First, NUBOMEDIA exposes its capabilities through a simple to use and intuitive API that can be used by non-expert developers on most popular client platforms such as smartphones and WWW browsers. Second, the NUBOMEDIA infrastructure is released using a flexible and attractive Free Open Source Software license, guaranteeing openness and neutrality.

As a core part in the center of the NUBOMEDIA architecture, Task 3.2 has designed the NUBOMEDIA Cross Layer Connectivity Manager (Leader TUB) as depicted in Figure 6.4.

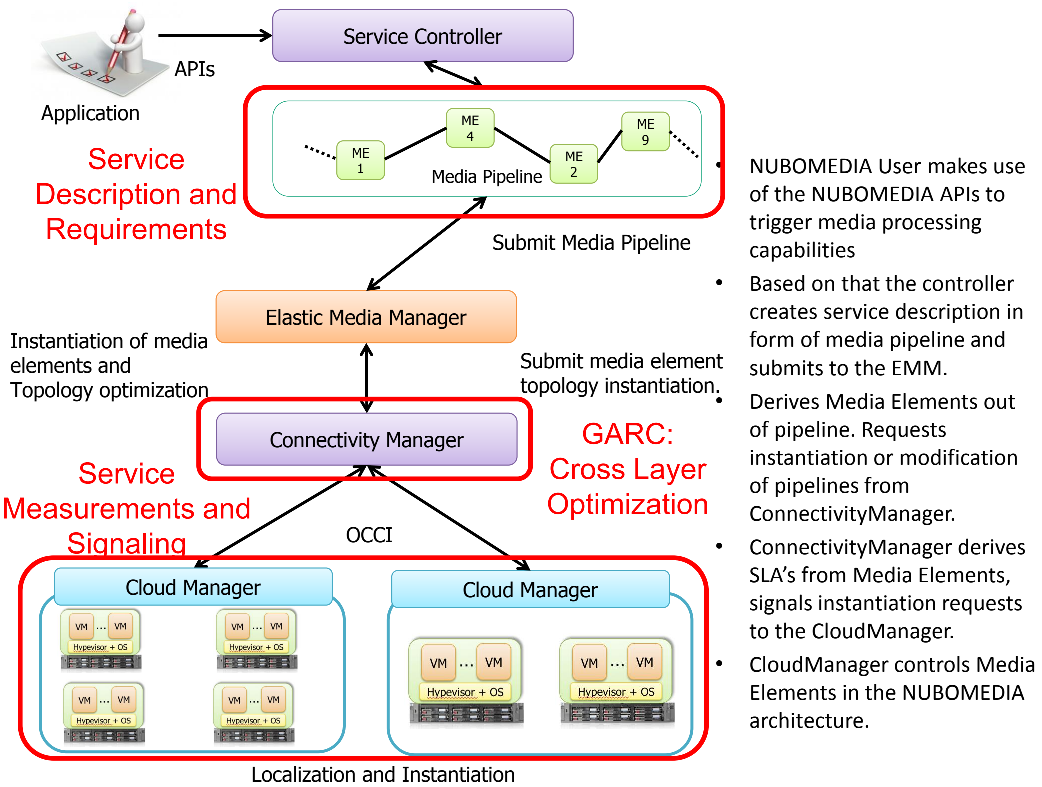

Figure 6.4: Mapping GARC Functionalities on NUBOMEDIA Architecture

To achieve these objectives, SDNs will be extended to support QoS in the network data path in order to fully control and manage connectivity between distributed resources.

On top of these objectives, this task will design and specify the required functionalities for supporting network-aware applications through optimized connectivity: that of Authentication, Authorization and Accounting (AAA) between end-devices and instance providers. SDN Switches and SDN Controllers will be managed for supporting QoS parameters from Media Services, pipelines and workflows.

The NUBOMEDIA Cross Layer Connectivity Manager controls SDNs and specially OpenFlow [13] within experimental sites. Service control mechanisms providing QoS guarantees for all stakeholders in the scenario are exposed through dedicated

APIs. This task contributes to the OpenFlow vision by providing the following additional ingredients for NUBOMEDIA:

a) Service-aware network support and data path optimization (efficiency, security, cost-optimization, etc.). The state of the network in terms of load derived from OF Switches is pushed into the NUBOMEDIA Cross Layer Connectivity Manager to maintain an active network topology state.

b) Network-aware application support through optimized connectivity and AAA. Prioritization of individual SDFs within SDN of signaling real-time over non-real-time communications. One key aspect of this work item is to identify the importance of the data traffic dynamically, accordingly to the services generating it and to the negotiated SLAs. Therefore, existing traffic pattern heuristics and application layer signaling will be selected and adapted according to the service requirements issued on the application and network layers. This should also enable the creation of a Call Admission Control (CAC) functionality.

Three main interfaces are foreseen for the NUBOMEDIA Cross Layer Connectivity Manager, which are directly derived from the GARC specification presented in Chapter 4.

- Interface to the the end devices: Intermediated through the NUBOMEDIA signaling plane, interaction with end-user terminals for QoS requirements and SLA statements are envisioned.

- Interface to the network (SDN): Network load situations are signaled towards the Connectivity Manager, in addition to events like new connection established or loss of bearer.

- Interface to the service: Media services are supported to register at the NUBOMEDIA Cross Layer Connectivity Manager indicating their level of QoS support/SLA. Media services instances signal parameters in real-time such as level of QoS in terms of bit-rate, frame-rate, resolution, packet-loss, jitter and latency. Using this information - and other external influences such as user demanded QoS statements - the Connectivity Manager is able to signal video streaming parameterization modifications towards the Media Service.

6.2.8 Summary of Academic Thesis Contributions

The necessity of this thesis work and academic thesis contributions have been outlined by indicating the influence of the thesis on the above-mentioned international ICT and Fraunhofer FOKUS/TU Berlin projects.

Ideas, concepts and implementation details in relation to GARC have been published [91, 37, 38, 39, 40, 41, 144, 42, 145] since 2011 and prototype evaluations [37, 92](2011) have been presented, which are now entering further ICT projects.

Some indicative aspects to measure the success of the thesis' contributions are the manifold positive publication evaluations by telecommunication experts serving as TPC members at international IEEE conferences. Their familiarity with the scope, positive and constructive evaluation comments and high evaluation marks have been taken as an indication of the success of this thesis work and contributions.

More than 25 scientific peer-reviewed publications have been published (as listed in the Annex B.1) and many industry talks have been held (as listed in the Annex B.4).

6.3 Delta between State of the Art and Thesis Contributions

This subsection describes and table 6.2 highlights the delta between the State of the Art and thesis contributions to 'Cross Layer Optimization'.

The table depicts the detailed comparison between the State of the art and thesis contributions referred to as Added Value. Several functional aspects of GARC have been validated, which are mentioned in the table columns as Cross Layer approaches. The individual technique for realizing such approaches is then explained too.

User initiated QoS has been presented in this thesis as a method for enhancing user experiences and for providing a richer Quality of Experience for the consumed service.

Common multimedia streaming services are designed to be non-network agnostic. Real-time network resource utilization and network situations are not taken into the QoS/QoE optimization process in existing solutions. Over The Top content compression and resolution scaling are today's only approaches.

GARC enhances this set of features through enabling a real-time and adaptive network as well as application layer adjustments. Dynamic and individual UE initiated QoS requests can be handled at runtime. The proposed solution has been validated for IEEE 802.11e networks, IMS and EPC architectures as well as SDN domains. A simplified approach in which the UE interaction is limited to a statement e.g. 'request better quality' has been realized. The transformation of generic requests into network specific QoS requests is done by GARC. Therefore no application or network technology details are required at the UE or server side application.

Network-aware Application Control enables application initiated service data flow optimizations and has been introduced as a method for optimizing connectivity taking the network state into consideration.

Adaptive streaming in today's networks is network unaware. One approach of Over The Top solutions is to stream HTTP content chunked in various bit rates at the same time. A list of available bit rates per stream is propagated in the form of a manifest file towards the client application. The client selects the bit rate according to the connection parameter. Short peak and overload situations cause direct modifications of adaptive OTT video streaming.

In comparison, GARC enables network-aware application control by extracting relevant network information. Different kinds of challenges on the data path might

Cross Layer Approach	Technique	State of the Art	Added Value
User-initiated QoS	Application parameter / adjusting video quality on a per flow basis	Not widely supported	Dynamic and individual UE initiated QoS requests at runtime; Real-time and adaptive network and application layer adjustments
Network-aware application service signaling	Application initiated service data flow optimization	Network independent OTT adaptive HTTP streaming	Real-time and dynamic network-aware application optimization
Application-aware networking	Cross Layer Optimization in addition to 3GPP policy control	3GPP PCC support for SIP based multimedia service for IMS over EPC; VLANs in operator networks	User-initiated QoS requests influence PCC decisions; Additional QoS Signaling is integrated into IMS streaming client
Application-aware flow based routing; Traffic Engineering	Application-aware routing	Not supported. IP packet routing is application independent and transparent	GARC enables application-aware data path optimization; Network events are exposed to subscribed applications through GARC
Demand-driven network adjustment; Network Management	Traffic Engineering and Network Management	Limited support for demand oriented scaling of the network topology and the service graph	GARC enables resource saving for CAPEX and OPEX through dynamic network scaling and elasticity support

Table 6.2: Delta between State of the Art and Thesis Contributions on 'Cross Layer Optimization'

be caused by different (external) influences in different parts of the network. Specific reactions have to be followed to address each of these challenges correctly. The identification of a particular overload situation in the access network might be solved by GARC through enforcing a vertical handover. The identification of a particular overload situation in the core network might be solved by GARC through enforcing changes of the dedicated bearer prioritization or re-routing. In addition to both situations, the application is also able to modify the service data rate / bitrate accordingly. GARC enables dynamic network-aware application optimizations on demand, through dynamic multimedia streaming parameter modifications. Once overload situations in parts of the network and potential for prioritization have been detected, GARC signals QoS offers towards a dedicated management application on the UE device. Thus the end user customer is able to grant or revoke the QoS offer. The result is signaled back as response from the UE towards GARC and is enforced in the network.

Application-aware Network Control in the Cross Layer approach is realized through applying the SDN concept on the transport layer within the access- and core network.

Cross Layer resource management is regarded in this aspect as an extra decision function and enhances 3GPP conform PCC additionally with novel features.

Current 3GG IMS and EPC solutions allow QoS enforcement only on the basis of static user subscription data. Alternative predefined SIP based services can be QoS supported statically.

The QoS policy enforcement in GARC for OpenFlow and IEEE 802.11e works together with an IMS client and multimedia SIP application server. Finally the QoS demands are requested via a 3GPP standardized Gx interface from GARC towards the 3GPP PCC. User initiated QoS enforcement can still be used for additionally enhancing IMS VoD streaming.

Elastic Network Design and Adaptive Flow Placement have been introduced as a method for scaling the virtual network functions and links according to the total bandwidth demanded.

Application parameters of networking policies, service levels, user profiles and energy consumption influence routing decisions.

IP packet routing is design application independent and transparent in today's networks. Network operator Operational Support Systems (OSS) has interfaces towards the network for management and control.

The network topology is controlled by GARC and is therefore seen as elastic and scalable. A novel aspect of the presented solution is the application-aware data path optimization. A topology of the physical network and related network elements is required. In particular, physical network elements are required as an underlying topology, on which routing schemes and traffic pattern can influence the actual network connectivity. Isolated links, aggregated sets of links or full switch/router line cards can be toggled between activation and deactivation. GARC introduces application-aware routing and optimized network utilization in a predefined topology. Network elements are controlled according to the bandwidth demand, which optimizes service delivery up to a certain degree of network saturation.

6.4 Experimental Use-Case Validation

After discussing the most relevant requirements in the previous Chapter 3, this section presents the use case definitions and validation scenarios for evaluating the concept and implementation of GARC. The technical setup and testbed topologies used for validating the prototype of GARC are presented in this section too. Multiple testbeds have been instantiated mainly to verify the heterogeneous network behavior.

At the time this thesis was written, no flexible QoS control schema was covering the high level, functional and non-functional requirements elaborated in Chapter 3.

Flexible service control is expected to become one of the key functionalities in future mobile network domains especially in critical infrastructures with real time requirements: industry, health, transport, public safety, energy, finance, entertainment, tourism, government services, etc.

Six Cross Layer Optimization validation scenarios have been realized, both to validate the correctness of GARC and to show the innovations as added value in contrast to today's telecommunication network and policy control architectures.

- Scenario 1: Network-aware Service Realization with GARC and GStreamer in 6.4.1.

- Scenario 2: GARC controls QoS per flow within an OpenFlow network in 6.4.2.

- Scenario 3: User profile and WiFi IEEE 802.11e network. The user profile is used to influence the IP Service Data Flow (SDF) based on QoS requests from the customer in 6.4.3.

- Scenario 4: SIP/IMS and OpenFlow network. Application layer signaling over SIP negotiates service data rates among SIP clients using an IMS. The P-CSCF of IMS signals negotiates the QoS parameters (SDP) over Diameter towards the PCC architecture of the network. In this case, GARC maps the SDP against the QoS parameters supported by the underlying OpenFlow network and enforces them. Requests are authenticated and authorized against user profiles stored in the network operator HSS/HLR in 6.4.4.

- Scenario 5: User initiated QoS request support in 3GPP EPC and PCC architectures is validated. An enhancement of the existing PCC architecture through GARC enables a fine granular per flow QoS control in 6.4.5.

- Scenario 6: Adaptive Flow Placement and Dynamic Network Design Module implementation, which has been validated through a simulation in 6.4.6.

The main idea behind the six scenarios is common and summarized as follows: GARC optimizes the E2E connectivity within heterogeneous access and core networks by maximizing a set of application parameters (list of codecs, list of supported bit rates, requirements) and network capabilities (routing, topology management, network priority level adjustment, etc.) adaptively. The three reference points of GARC (network, service, UE) as outlined in Chapter 4 under 4.6 are validated as part of these scenarios and their added value is pointed out. Improved network measurement functionality in all scenarios is realized as DPI/TDF, which monitors bandwidth utilization and may trigger an increase or decrease of the Service Data Flow (SDF) rate. Modifications of the SDF include bit rate, frame rate and resolution. No interaction on the client side is required, which makes the solution backwards-compatible with existing end user equipments.

6.4.1 Network Aware Service Realization with GARC

An adaptive Network Aware Service has been realized with GStreamer, which adjusts the service data rate according to the available bandwidth and network capacity. Network services such as DPI or TDF indicate the packet loss ratio for a given flow. DPI or TDF then signals that information towards GARC over the GARC-to-network reference point, where the information is evaluated and might cause adjustments to the service in turn.

Scenario Description An adaptive network layer initiated service controller scenario is depicted in Figure 6.5.

Preconditions The following preconditions are assumed during the GARC initiation.

- Service registration at GARC: Application parameters are signaled as a list of codecs, list of supported bit rates, resolution, frame-rate, etc.
- Network registration: Network capabilities such as network priority level, QoS-Class-Identifier (QCI) support, etc. are registered at GARC or through auto-discovery.

No interaction on the client side nor any API trigger is required.

Scenario Schedule The order of the individual steps for this scenario is listed as follows:

1. Service invocation from user; data path establishment between UE and server over IP network such as multimedia connection, cloud synchronization or an enterprise VPN connection.

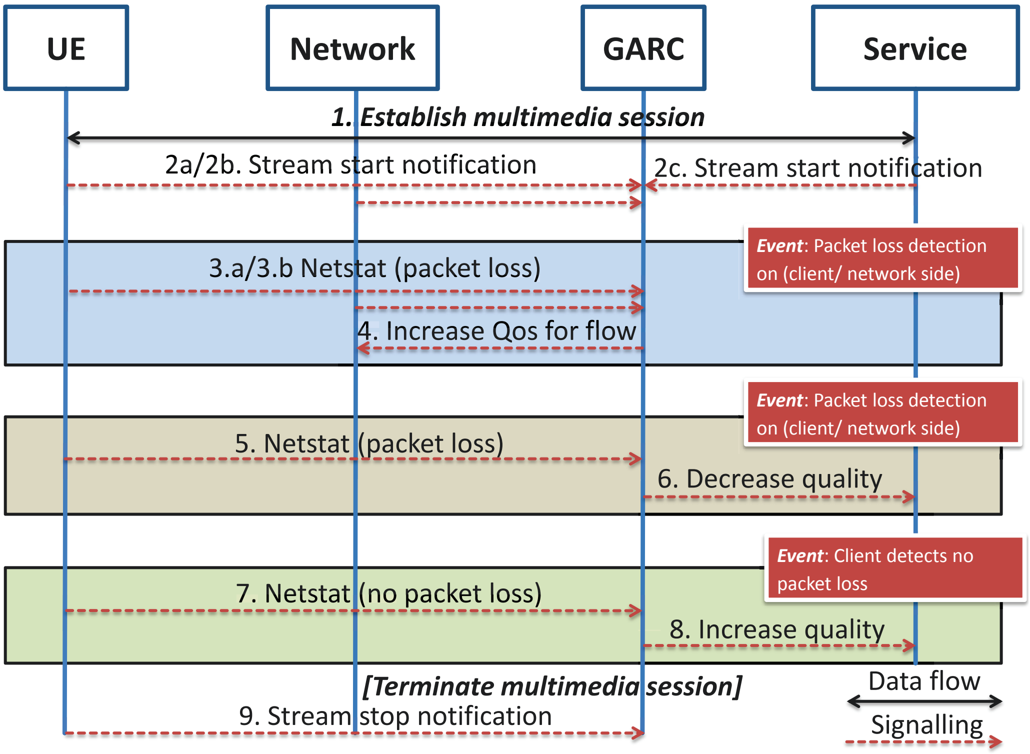

Figure 6.5: Network-Aware Service Control Mechanisms

2. The trusted service reports the new service invocation towards GARC by signaling userID, TFT (source and destination port, port, protocol) and application parameters.

3. **Network utilization increases**

4. The network monitors (running at the client machine) high packet loss on the data path close to the user temporarily.

5. Passing a threshold of packet loss ratio per time interval triggers notification by signaling TFT from the network towards GARC by reporting significant packet loss on a specific data stream.

6. GARC maps TFT to internal bearer table and identifies the user, maps user-profile/credentials to service QoS demands and then computes an optimization strategy.

7. GARC may react by a) (first) increasing network prioritization level until reaching the max QoS or b) (second) reducing bit rate or resolution in order to decrease the bandwidth demand and then enhance QoE in turn.

8. **Network utilization decreases**
9. Bandwidth probing on the client reports available network resources to GARC.
10. GARC triggers service to increase Service Data Rate slowly.
11. Service-data-rate is increasing until packet-loss-monitoring tool reports notification threshold towards GARC.
12. GARC freezes service-data-rate-level temporarily for the time x.
13. **continuing scenarios following from this point on** a) **Network utilization increases** Start over with step #4. b) **Network utilization decreases further** Start over with step #9 / step #10.

No interaction on the client side; no API trigger required.

6.4.2 GARC, OpenFlow and Adaptive Streaming

A closed network with five virtual machines for the OpenFlow Controller, Switch, two hosts and GARC was instantiated for validating the features of GARC with SDN OpenFlow. Network initiated QoS offers initiated by GARC towards the UE are validated with this scenario.

6.4.2.1 OpenFlow Testbed Environment

A testbed for validating Software-Defined-Networks was instantiated to perform test cases with a focus on congestion control on one link between two OpenFlow switches. The topology of the testbed has been designed to validate flexible QoS through GARC in overloaded networks. Two services running on the host machine (GStreamer and IPerf) send data traffic into the virtualized environment through OpenFlow Switches B and A and further on to one of the destinations Host 1 or Host 2. The experimental setup is kept generic and is repeatable with hardware and software switches.

The technical setup for OpenFlow measurements consists of one physical host machine and multiple virtual machines as depicted in Figure 6.6.

The hard- and software for the host are the following: DELL Precision WorkStation T3500, Ubuntu 11.10, 2x4 Intel Xeon CPU W3530@2.800GHz, 18GB DIMM DDR3. In addition, we've reserved virtualized hardware and software resources as follows for all virtual machines: VMware Virtual Platform, Ubuntu 10.10 /11.10, 1-2 Intel Xeon CPU W3530@2.800GHz, 0.5 - 2 GB RAM.

6.4.2.2 Scenario Schedule and Experimental Validation

Two IPerf-Streams (representing parallel background data traffic in the network) are sent between the host machine and Host 1. One TCP flow represents background traffic and a second UDP stream represents a real-time multimedia streaming application.

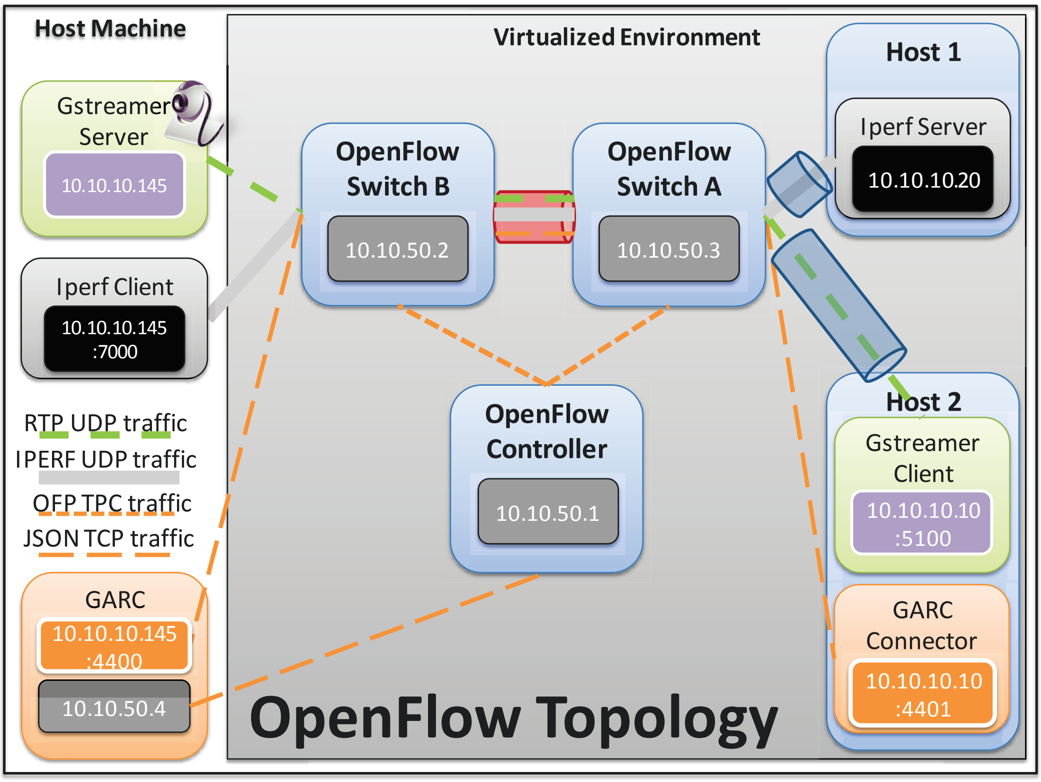

Figure 6.6: Technical Setup Demonstrating Software-Defined-Networks

Only one (blue line) of the two flows is started at 4:11:00 as depicted in Figure 6.7 with a data rate of 300 kbit/s.

At the same time, an adaptive GStreamer service developed as part of this thesis has been established between Host Machine and Host 2. The link between OpenFlow switch A and OpenFlow switch B is limited artificially and is therefore dimensioned in a smaller capacity than the sum of all three flows requires. Therefore packet loss will occur on this link in the topology.

A network monitoring system (DPI/TDF) has been placed on the client side to indicate packet loss on the last hop. These periodic network measurements are signaled every 5 seconds from the DPI/TDF to GARC, responding with the packet loss ratio per flow.

The adaptive GStreamer flow is depicted as a red line, which increases up to a predefined maximum service data rate of 1MB/s.

The packet-loss threshold is adjusted at 3% to be robust against minimal packet-loss caused by external reasons such as temporarily overload of the physical host machine.

The state stabilization is initialized with an iteration of 4 cycles before decisions for bit rate modifications are signaled either to the service or into the network.

Network and services are in a stable state between 4:11:41 and 4:13:01 of the experiment. A new IPerf stream is started at 4:13:02, which utilizes the link capacity and causes packet loss for other flows in the network.

Packet loss can be noticed in the GStreamer live streaming web cam video, which begins with stalling. The service data rate is reduced for all services.

An QoS offer triggering notification is initialized at 75% packet-loss before sending the notification from GARC towards the UE at 4:13:21.

The UE accepted the QoS offer at around 4:13:30, which is signaled back to GARC for network enforcement.

6.4.2.3 Result Discussion

Figure 6.7 depicts the scenario type OpenFlow. The total UDP data traffic is marked black, IPERF (900 kbit/s) and IPERF (300 kbit/s) are marked green and blue and the adaptive GStreamer video stream is marked red.

The re-prioritization described above causes a service rate growth of the adaptive GStreamer service in turn. A slow start and stepwise growth can be recognized in the graph of the GStreamer service.

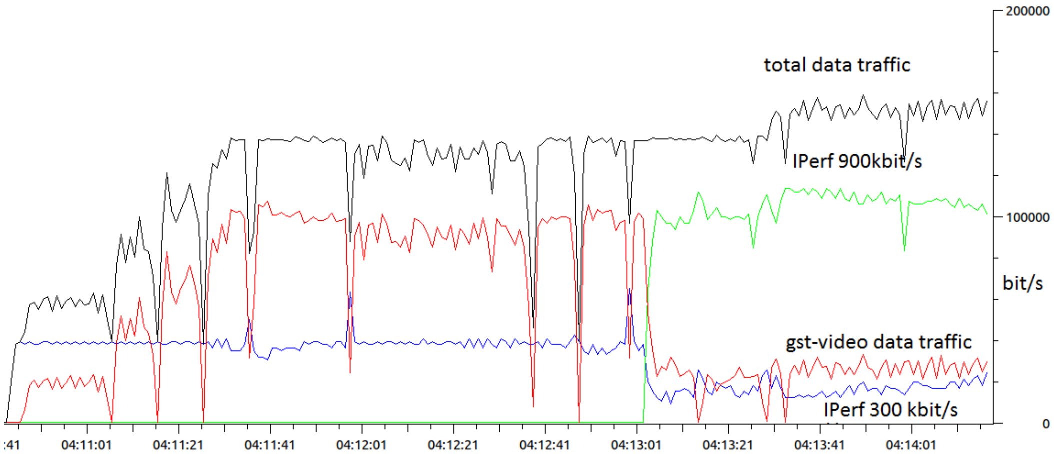

Figure 6.7: OpenFlow Use-Case Scenario of GARC

The parameters and timers are all flexibly defined and are optimized later on. Previous measurements of the same scenario showed similar results.

6.4.3 GARC and 802.11e - WiFi - EDCA

A use case study on QoS in the WiFi 802.11e networks using GARC is presented in this subsection. QoS control in WiFi networks is challenging because of the missing centralized coordination as in mobile networks. Nevertheless, opportunities for controlling the downlink in WiFi exist and are explained in the following.

6.4.3.1 WiFi 802.11e Testbed Environment

Technical setup for 802.11e measurements consists of one host machine and multiple virtual machines as depicted in Figure 6.8.

The following hard- and software has been selected for the client: Thinkpad T60, Ubuntu 12.04LTS, Genuine Intel(R) CPU T2500 2.00GHz, 4 GB S0DIMM DDR2, Intel PRO/Wireless 3945ABG.

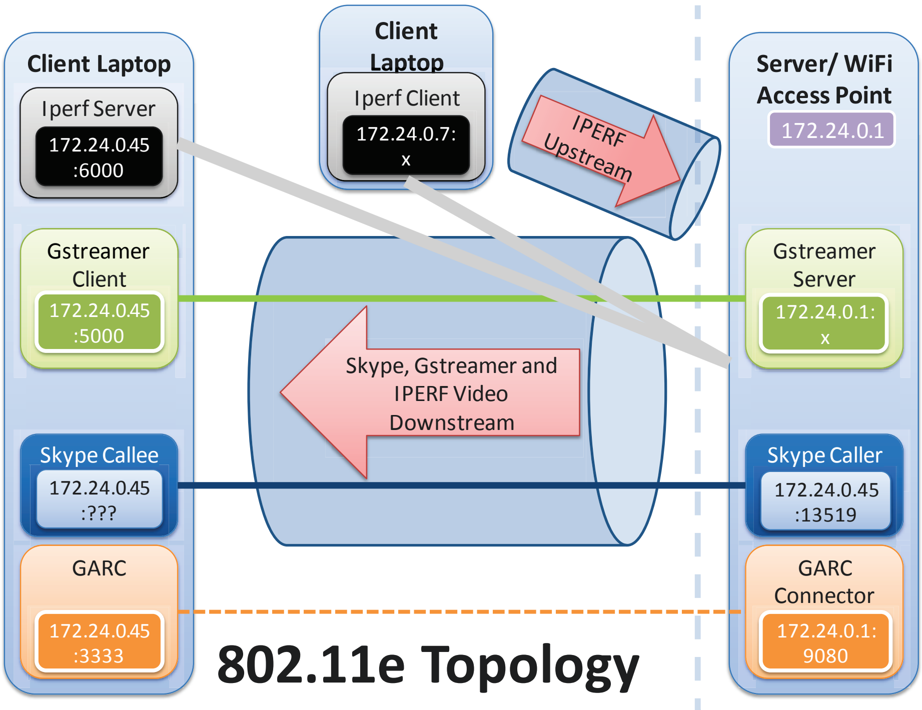

Figure 6.8: Technical Topology Setup Demonstrating WiFi 802.11e

We've selected the following hard- and software for the server: ThinkPad X200, ubuntu 12.04LTS, Intel(R) Core(TM)2 Duo CPU P8800 2.66GHz, D-LINK DWA-160 802.11n USB-adapter, 4 GB DDR3.

The network topology for the WLAN demonstration scenario is shown in Figure 6.9. It consists of two networks - WLAN and Ethernet - each of them connect two machines (with the Ethernet also providing Internet access). Machine A (entitled Ethernet) is running the GARC framework and is attached to Ethernet. Machine B (entitled AccessPoint) is the WLAN AP, which contains both an instance of the proxy and a WLAN Adapter. Machine B also has the role of a router between the WLAN hosts and the AF/Internet. The User Equipment has been implemented as a WLAN UE.

The diagram represents a topology setup, in which two flows (blue/dashed and green/dotted line) are both connected over WLAN to the same Access Point. Due to the limited capacity of the radio link, packet loss occurs even during full utilization of the radio link. The actual scenario involved four flows, each corresponding to a

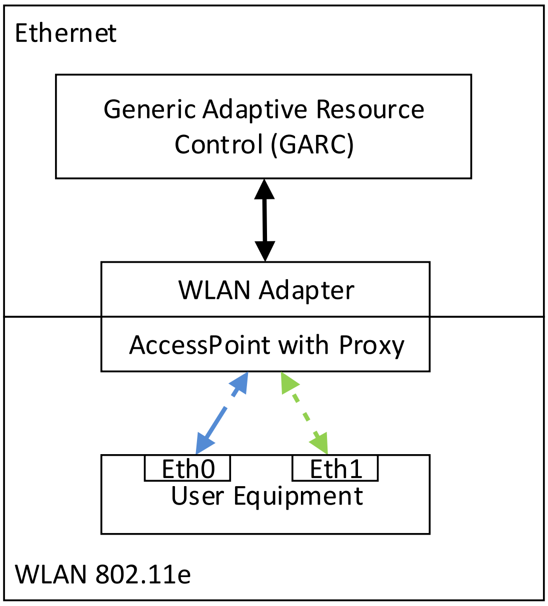

Figure 6.9: Technical Setup for Validating GARC over 802.11e

different traffic class. The general idea was to start four equal flows between the AP and the UE and then monitor the ways setting the QoS affected their performance. The tool used to simulate the traffic is IPerf, which can be used both for UDP and TCP connections with customizable bit rates and lifetimes. IPerf also provides the possibility to modify the DSCP field in the IP header, which validates the correct configuration of the AP to recognize QoS on a novel per flow basis.

As an untrusted party of the end-to-end communication channel, the client device should not be regarded as an independent and trustworthy information source, but the network is regarded as such. However, a packet-loss monitoring component has been specified and designed as a network layer service on the User-Equipment (UE) within our prototype, in order to measure packet loss on the very last hop.

6.4.3.2 Scenario Schedule and Experimental Validation

The OpenFlow and WiFi 802.11e setup variants are validated using the same use-case scenario with seven steps, which are explained for the OpenFlow variant exemplary. Multiple flows are instantiated on a best-effort basis between the client and the service representing different Service-Data-Flows (SDF). One of the SDFs is a real-time webcam video stream using an own implementation of an adaptive GStreamer real-time video service. This service consists of a server and client part: gst-server and gst-client.

We initialized a reference video stream with Skype in parallel to compare the adaptive behavior of our streaming approach during load situations in the network.

Due to hardware limitations caused by accessing only one single webcam at a point in time within VMware, we were forced to take an IPerf stream for the OpenFlow scenario and used the Skype reference video in the WiFi scenario. The WiFi scenario uses a laptop supporting access to two webcams in parallel. The virtualized environment does not support this feature.

The steps of the scenario measured in seconds are:

1. An adaptive multimedia webcam live-stream is started in an underutilized network at T10s. The initial bit rate of the connection is low and grows continuously towards the maximum bitrate until it saturates on the maximum.

2. An reference IPerf stream with 800 kbit/s is started in the background.

3. A second IPerf stream with 4000 kbit/s utilizes the network link at T95s fully, which degrades the IPerf stream with 800 kbit/s and the webcam stream in return.

4. Packet-loss is measured through distributed measurement probes at the device, in the network and on server side. These probes report packet-loss towards an JSON monitoring interface of GARC.

5. On receiving the packet-loss event in GARC over a significant time duration defined through the service provider or network operator, the GARC Control and Optimization module analyzes the possible reactions and determines an optimal policy decision presented in 4.5.1. Either the priority of the SDF is changed, the path in the network is modified or the service rate is adapted.

6. The gst-server webcam service adapts the bit rate to a lower level after four cycles of a predefined interval in our two validation scenarios and reaches a stable video playback. The reference stream is challenged by high packet-loss in turn, over a prioritized signaling bearer.

7. GARC signals QoS Offer notifications towards GARC subscribed applications on the terminal of the UE, for improving the bandwidth. In our scenario, the user accepts the offer at T175s.

8. The adaptive streaming client was designed to avoid oscillation in case of traffic bursts, therefore a stall period without any bit rate adaptation can be recognized in T175s until T200s.

9. From T200s until T300 the bit rate increases further, caused by the higher bandwidth prioritization, which in turn leads to no packet-loss.

6.4.3.3 Result Discussion

Figure 6.10 depicts the scenario type WiFi 802.11e. The total UDP data traffic is marked black, IPERF green GStreamer red and Skype blue.

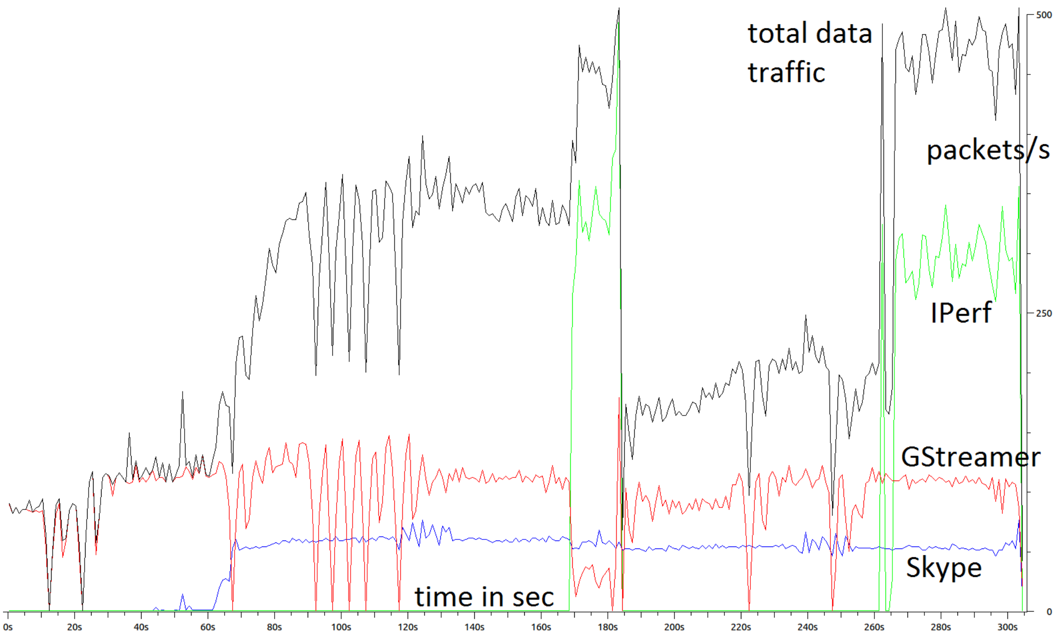

Figure 6.10: WiFi Use-Case Scenario of GARC

The depicted scenario is aligned with the schedule 6.4.1 described above. Packet loss is caused by overloading the WiFi access point. The adaptive GStreamer and Skype service reduce the service data rate until the point (from t170s), in which the UE accepts the QoS offer (t180s), which triggers the equal prioritization of both services.

From t250s on, both services increase their service data rate again. The adaptive Gstreamer service increases its service faster to a maximum. Both videos are displayed fluently without stalling and artifacts.

The results of a second evaluation are shown in Figure 6.11 and have been repeated five times with equal results. All the flows start equal with traffic class 0 (equals default, best-effort, legacy) in each of the tests and are then assigned to different QoS classes simultaneously. There were four flows active: two with TCP and two with UDP. In the TCP tests, the flows were all trying to send as much data as possible and as shown, the results varied noticeably (a lot of this was caused by interference). In contrast, the UDP flows (each of which requested about a third of the available bandwidth) managed to transport more data during an equal amount of time.

t0 Start experiment with four independent TCP flows without any QoS class label.

t80 Assign each flow to one of four QoS classes: Voice, Video, Best Effort and Background

t130 Remove QoS classes from flows. End of experiment.

This scenario also highlighted an interesting side-effect of high traffic classes in WLAN: using DSCP fields for traffic prioritization increases the total available bandwidth in the network. This effect can be explained with the properties of these classes, such as the smaller minimum Contention Window (CW), which results in an increase in the amount of time the stations are transmitting. The size of the CW is reduced, data can be sent faster and the overall data transport efficiency grows.

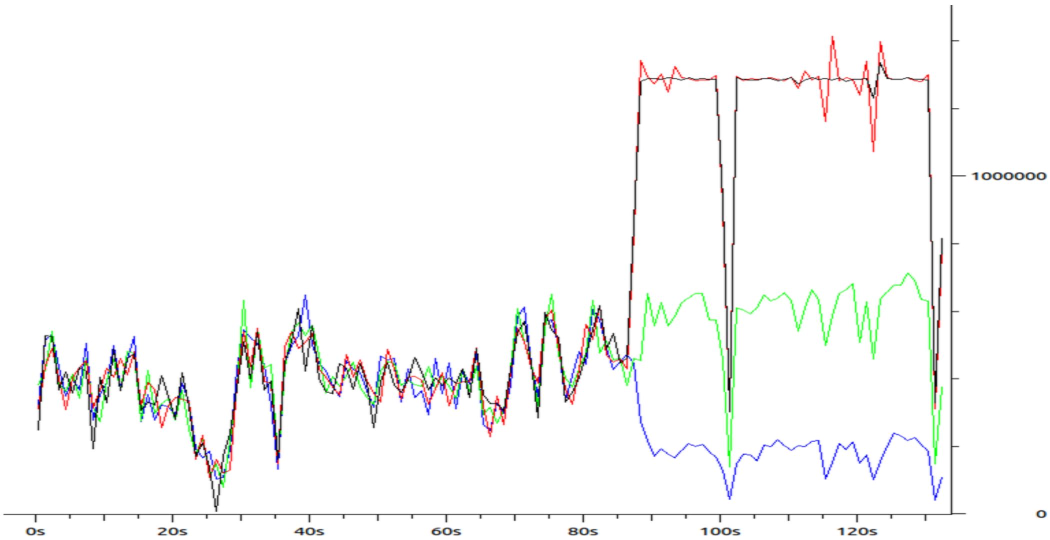

Figure 6.11: Experiment Validation with GARC and DCP IEEE 802.11e

The usage of Policy Control improves bandwidth resource utilization of IP data traffic significantly. GARC also enriches the feature spectrum for QoS support in 802.11e access points. Enhanced distributed channel access (EDCA) increases the average likelihood of a high priority packet being sent in comparison to a low priority packet. Radio control parameters such asCW, shorter arbitration inter-frame space (AIFS), contention-free access to the channel for a period called a Transmit Opportunity (TXOP) are modified for packets of a given stream for prioritization.

The results within this experiment validate the correctness of the GARC functionality and the ability to influence QoS using GARC.

Different measurements of the same experiment have shown similar results.

6.4.4 GARC, 3GPP IMS and OpenFlow

This use case describes a scenario in which the Policy Control and Charging architecture of an IP Multimedia Subsystem is enhanced with GARC Cross Layer optimization functions. The aim of this use case is to join the 3GPP telco and SDN OpenFlow domain by supporting VoD session setup and termination using SIP signaling and Diameter protocols on top of an OpenFlow network. Initially a SIP session is initiated between a SIP client (UE) and a VoD Application Server (AS) using the OpenIMSCore [166]. The topology of this use case validation can be seen in Figure 6.12 with all its related components. The Java version of the Diameter peer (JDiameterPeer) of GARC subscribes to the PCRF for retrieving session information after negotiation. After successfully establishing the session over SIP, the VoD AS signals the negotiated QoS parameter (derived out of the SDP) over the Diameter Rx interface towards the PCRF. The PCRF in turn, validates the request and signals QoS enforcement and bearer binding and reporting parameters over the two Diameter reference points Gx and Gxx towards the subscribed network element. This network element is GARC, which translates 3GPP specific QoS parameters into OpenFlow specific ones, which are then forwarded towards the OpenFlow Controller.

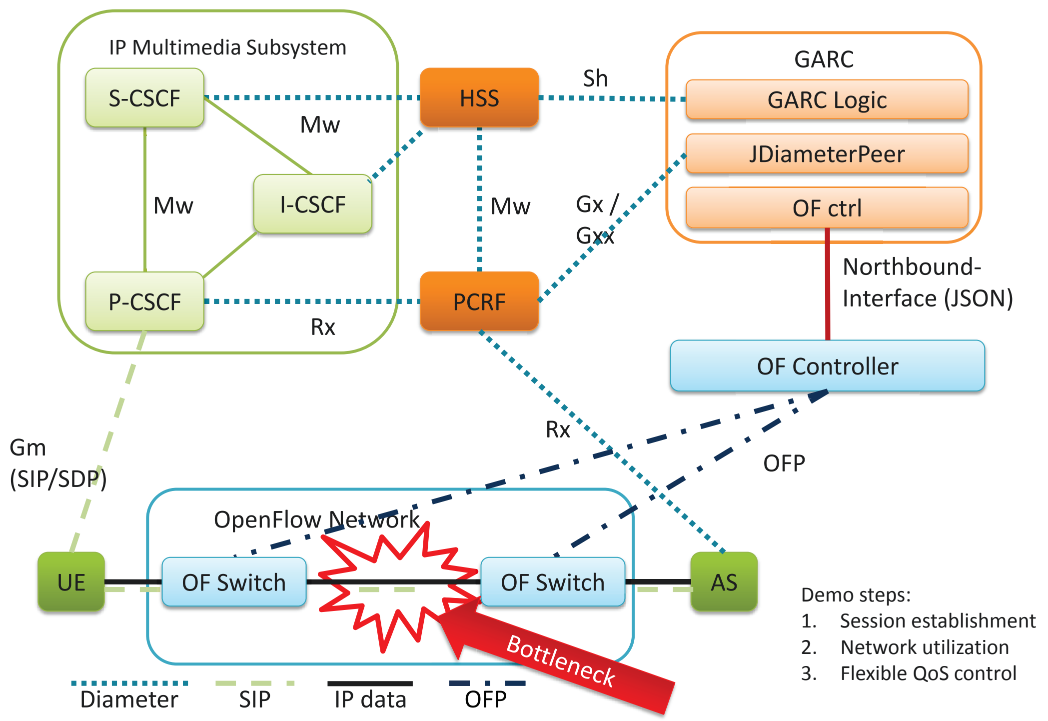

Figure 6.12: 3GPP IMS Use-Case Topology with GARC

The OpenFlow Controller monitors the OpenFlow network for overload situations and congestions by analyzing the packet drop ratio of all OF Switch queues. The prioritization level is terminated according to the user profile, which is queried from the HSS over the Diameter Sh reference point. The logic implemented in GARC compared the prioritization level of the individual Service Data Flow per user.

The link between the two OpenFlow Switches is artificially limited to 100 kbit/s in order to cause high packet loss with four streams each requiring 50 kbit/s.

GARC is able to provision and enforce the 3GPP QCI level within an OpenFlow network and therefore adjusting the QoS flexibly per flow.

The validation of the Cross Layer approach applied on the 3GPP IP Multimedia Subsystem has been evaluated by observations and measurements. A wireshark trace proved the correctness of the scenario including signaling flow and RTP data messages within the communication system. The scenario includes a Video on Demand (VoD) data stream that is initiated (1) and terminated (21) through the end user. SIP signaling negotiates the service specific parameters (codecs, resolution, endpoints, etc.). The Diameter peer of GARC has been configured to subscribe to the PCRF of the IMS. All subscribed parties receive notifications from the PCRF for subscribed events according to the 3GPP standard. The most relevant step in this message sequence list is the signaling of QoS related parameters for enforcement on the gateways. This step is listed as (8) in the list below and depicts the border between 3GPP and OpenFlow domains. The 3GPP conform Gx Diameter signaling is transformed by GARC into an OpenFlow specific network parameter.

Figure 5.3 in Chapter 5 depicts QoS mapping to Service Data Flows according to the measurement.

1. SIP IMS registration of Caller and AS
2. (User initiated service invocation)
3. SIP INVITE Caller to AS signaling and QoS parameter negotiation using SDP
4. Rx Diameter request from AS to IMS: P-CSCF transforms 200 OK SIP/SDP into PCRF AA-Request
5. Sp Diameter User-DataRequest/-Answer exchange between PCRF and HSS/SPR
6. Rx Diameter AA-Answer (DIAMETER SUCCESS 2001) between PCRF and P-CSCF
7. SIP 200 OK, with session description
8. Gx Diameter message between PCRF and GARC signaling the multimedia related parameter enforcement
9. Gy/z Diameter Accounting Request/Answer between PCRF and Charging System
10. OFP: GARC to OFC signaling for changing prioritization though MODFLOW queue modification message
11. SIP ACK
12. RTP user data transport initiated
13. (User initiated service termination)
14. SIP BYE

15. RTP user data transport terminated
16. Gy/z Diameter Accounting Request between PCRF and Charging System
17. SIP 200 OK
18. Rx Diameter Session-TerminationRequest between P-CSCF and PCRF
19. Gy/z Diameter Accounting Answer between PCRF and Charging System
20. Rx Diameter Session-TerminationAnswer between PCRF and P-CSCF
21. SIP IMS de-registration of Caller and AS

The following Table 6.3 maps 3GPP SDP to SDN / OpenFlow QoS representations.

SDP Field	**Type**	**Description**	**OpenFlow Equivalent**
Bandwidth	b	Proposed bw limits	OF Queue
Timing	t	Start / End times	Hard timeout for a flow
Connection	c	Connection Type and Address	nw_protocol / nw_src
Media Description	m	Media definitions (incl. protocol and port)	Transport protocol and port (tp_src)
Attribute Send/Receive	a	Sendsrcv	Create unidirectional flow in specific direction
Origin	o	Originators Name and Identifiers	nw_src

Table 6.3: 3GPP SDP Parameter Mapping to OpenFlow

In addition and in contrast to the existing solutions, user demand QoS requirements can be integrated into the policy decision process.

6.4.4.1 Scenario Schedule and Experimental Validation

The full experiment is depicted in Figure 6.13 and has a total duration of 180 seconds and contains five parts, in which SIP negotiated QoS is used to control the priority of each flow. The setup is configured with four flows and four different QoS classes - other parameters are possible.

t0 Start experiment with four independent SIP based VoD flows without any QoS class label.

t20 Assign each flow to one of four QoS classes supporting minimal bandwidth guarantees.

t80 Change QoS class mapping of flows.

140 Remove QoS classes from flows. flows swing into a stable and equal bandwidth level.

t180 End of the experiment. All connections are closed.

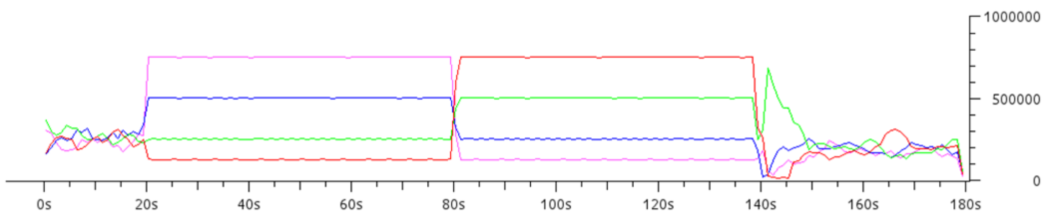

Figure 6.13: Experiment Validation with IMS, GARC and OpenFlow

Figure 6.13 presents the results of four independent SIP based VoD connections, which are prioritized twice at different points in time with different QoS classes.

GARC controls the QoS level over an OpenFlow controller, which in turn assigns specific queues to each flow representing the QoS level. Each queue is adjusted to follow specific minimal and maximal bandwidth requirements.

6.4.4.2 Result Discussion

The results within this experiment validate the correctness of the GARC functionality and the ability to influence QoS using GARC.

1. $OFP-FLOW-STATS-REQUEST$ (also $QUEUE-STATS$, $PORT-STATS$, etc). The OF Controller periodically sends a request for network statistics to the OF Switches.

2. $OFP-FLOW-STATS-REPLY$. Each response contains queue and port statistics on data rate and packet drop ratio.

3. $NETWORK-STATS$. The OF Controller exposes the statistic collection towards GARC.

4. Analyze network state in regard to congestion, packet loss per port, etc. Compute multiple possible solutions and find the optimal solution given a set of input parameters. Signal optimization policy towards decision point of the network operator or to the enforcement point directly.

The individual steps of the scenario sequences are outlined in the following. The validation has been performed with the POX [158] OpenFlow controller in the github version (June 2012) together with OpenVSwitch [173] in version 2.0.0. The controller has been extended with an application for subscribing to network events. The whole communication between GARC and the OpenFlow Controller has been realized. OpenFlow messages between switch and controller have not been modified.

1. $OFP - PACKET - IN$: The OF Switch receives the first packet of a new flow, which has no entry in the table to forward it, pushes the packet on to the OF Controller.

2. $ROUTE - REQUEST$: The OF Controller receives the packet, forwards it on to the application running on the OF Controller, which in turn extracts the TFT for the to the Flow-Placement function in GARC.

3. $ROUTE - TYPE - REQUEST$: The Flow-Placement function collects all relevant information for the new flow from GARC.

4. $DatabaseLookup$: GARC performs a lookup for the given parameters in the user and service databases, to find out if the TFT contains IP/Port of a known User/Service to estimate needed bandwidth and QoS level.

5. $ROUTE{-}TYPE{-}REPLY$: Transport required information regarding bandwidth and QoS level.

6. $Calculateoptimalroute$: Calculation of the optimal route in the network, based on full topology information (incl. cost), and the User/Service meta data.

7. $ROUTE - RESPONSE$: Answer to the controller (FP-module in the controller), containing the route for the requested packet.

8. $OFP - PACKET - OUT$: The propagation of new flow characteristics to all switches on the path (so no additional Packet-In event/message delays the session setup).

Different measurements of the same experiment have shown similar results.

6.4.5 User Demanded QoS, GARC and 3GPP EPC

Concepts for User Demanded QoS as contributions of the thesis have been published in [38], which includes parts of these following ideas. A new core network component is necessary, in order to introduce a flexible method to compose and invoke network functionalities from the UE in a dynami way. GARC has been introduced in the 3GPP control plane, which works with 3GPP and non-3GPP networks. Each UE is able to state generalized resource requirements to GARC, which in turn validates these requests and transforms the generalized into access network specific IP-CAN

Bearer establishment, modification or termination requests. The following stages in Figure 6.14 have been defined in order to realize a UE initiated bearer modification:

Stage 1: The UE is successfully attached to the mobile network and a default IP-CAN Bearer is established.

Stage 2: The UE sends a generalized QoS Modification Request to GARC and states its QoS requirements. The signaling bearer transports all signaling messages between UE and core network at this point.

Stage 3: GARC validates the request, determines the current access network related to the established bearer and finally translates the generalized into access network specific QoS requirements.

Stage 4: GARC signals the AN specific QoS parameter to the PCRF using a service specific authentication and authentication request (AAR). This procedure is aligned to the Rx interface between the Application Function and PCRF within the EPC.

Stage 5&6: The PCRF authenticates and authorizes the UE request querying the Subscription Profile Repository (SPR).

Stage 7&8: After retrieving the UE profile, the PCRF determines a decision to either grant or revoke the request, and returns a AA-Answer.

Stage 9&10: In case the request is granted, all gateways are notified by transmitting a new policy (Diameter Re-Auth Request (RAR)) to all gateways involved in transporting the flow.

Stage 11: All effected gateways - PDN and access network specific gateways - install, modify or remove rules using this new policy and subscribe for a event notification. The EPS bearer is modified and service data flows receive a different treatment based on the changes in the network.

Stage 12&13: The gateways return a Re-Auth-Answer to the PCRF to indicate the success or failure of the process.

Stage 14: In case network changes effect a subscribed bearer, the event raises a notification addressed to the PCRF, which may adopt the QoS level.

UE Initiated QoS Requests In order to provide a broader spectrum of network functionalities, the operator controlled network functionalities needed to be exposed and invoked in a dynamic way. GARC controls and manages such (virtual) network functions (NF) by invoking specify NF for a given TFT related to a service invoked by the UE. The missing flexibility of QoS diversification in today's networks is broken up through the introduction of the new GARC component. User demanded and operator controlled individual QoS per flow, service or user is supported through policy enforcement on the gateways. These policies are derived from user initiated intent statements. Such intent statements are formulated in a generalized way in order to ensure network transparency. Intent statements are routed over the signaling bearer from the UE to GARC. The UE either signals its requirements directly on demand from the UE to GARC and states the QoS for each individual service data flow separately, or pushes its demanded static QoS levels to GARC for a session or a

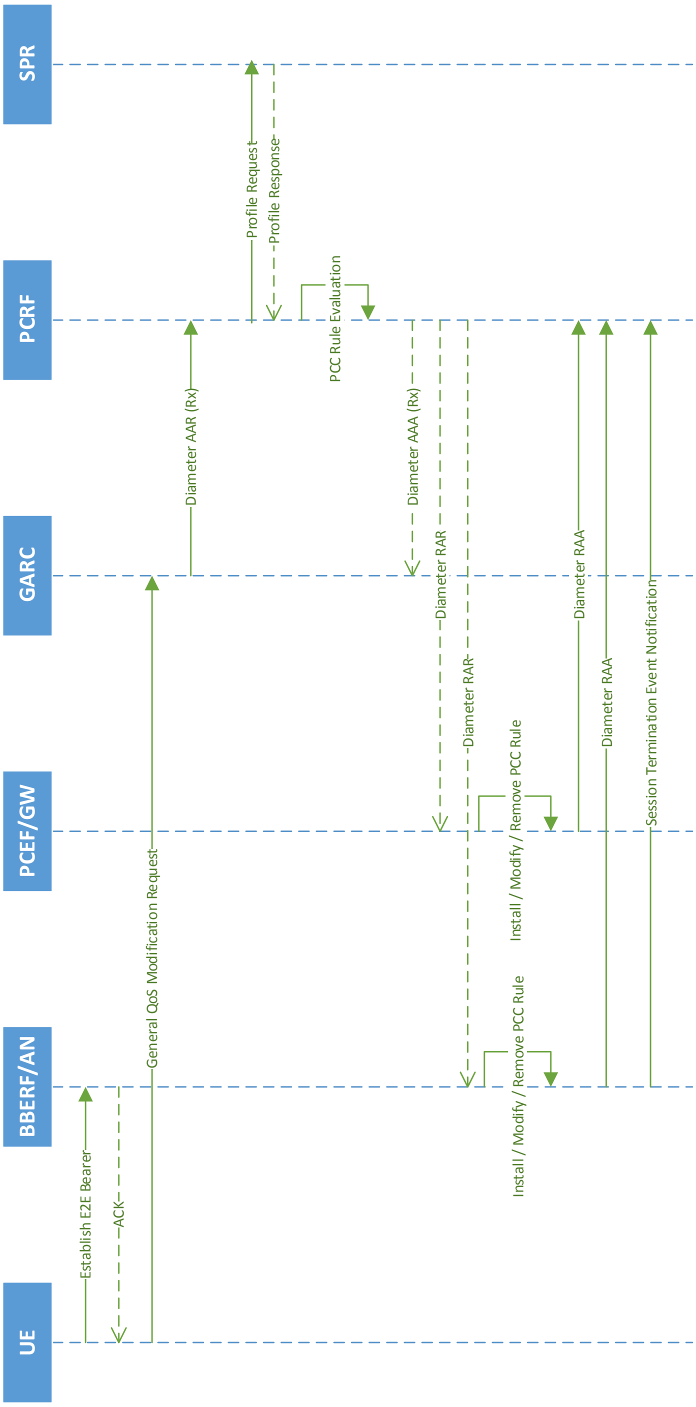

Figure 6.14: 3GPP EPC Use-Case Scenario Validation with GARC

given time period. These user intent statements demand specific QoS classes, which in turn have different (technical) requirements on the underlying network, UE or executed service. The AAA component in the connectivity plane validates the intent together with the user credentials. These generalized service layer requirements are forwarded next to connection information (Traffic Flow Templates (TFT)) on to GARC. GARC is aware of the underlying network capabilities of the UE and receives the service layer requirements. GARC negotiates between the network and service layer in order to maximize the connection trade-off by identifying the most suitable combination of functionalities.

This process is regarded as highly complex and may approximate good solutions instead of searching for 'the best solution' for a given connection. The best solution is selected out of a set of candidate solutions through an algorithm, which is, in the first realization, a prioritized list. Due to the flexibility of GARC, distinct algorithms can be supported for different network operators.

Once identified and granted, the selected network functionalities are enforced on the gateways. In case of the selected set of functionalities is revoked, GARC notifies the UE outlining the reason for revoking. A modification of the selected network functionalities without the critical parts is invoked from GARC in case of failures while invoking the previous set of functionalities.

Network Initiated QoS Offers A second variant for QoS optimization, depicted in Figure 6.15, has been defined by re-designing the message flows. This example includes GARC with network monitoring functionalities of the data plane. Packet loss ratio has been measured, other parameters are also possible such as delay, jitter, etc.

During the initialization phase, UE and service register at GARC in step 1. Both indicate their individual characteristics in form of parameters. A session is established in step 2 and GARC monitors the network state by subscribing to bearer event notifications in step 3.

In case of overload situations, the applied QoS per bearer might be violated and events are initialized from the BBERF. On receipt of the event at the PCRF, all subscribed instances for this specific bearer are notified such as GARC. A proof of the user profile within the HSS over Diameter Sp through querying by GARC is performed in steps 5 and 6. Upon positive evaluation, a QoS offer is sent in step 7 from GARC to the UE or application running on the end user device. The answer in step 8 is validated again and might cause Credit-Control Requests and Answers in step 10 and 11 to increase the QoS for a bearer in step 12. The QoS level ends upon terminating the service data flow, when not specified otherwise.

6.4.6 Adaptive Flow Placement and Dynamic Network Design

This section outlines the validation setup first and then discusses the computational results. Ideas and concepts of GARC presented in the next subsections have been published successfully under IEEE ICCCN [42] and SDN4FNS 2013 [145]and was also part of a Master Thesis at TU Berlin [146] in cooperation with Fraunhofer Institute FOKUS. The Cross Layer aspect in this validation validates a novel approach

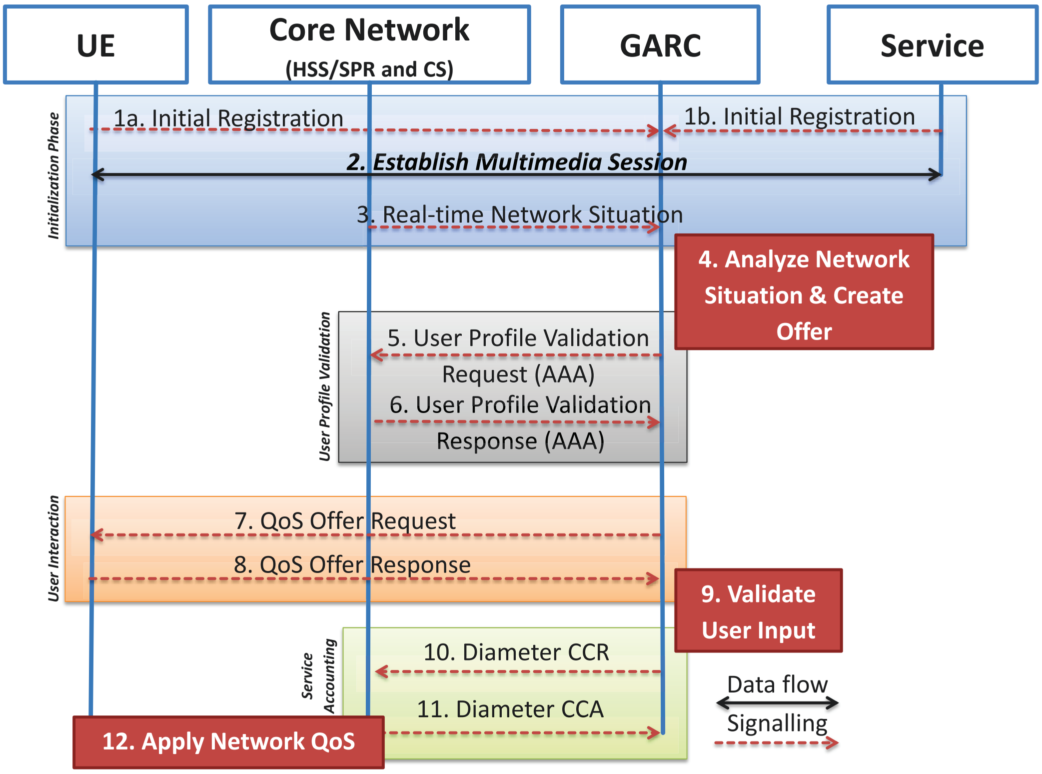

Figure 6.15: Network Initiated QoS with 3GPP EPC Architecture

for network-aware applications.

6.4.6.1 Validation Setup

The model from Section 4.5.5 was implemented in C++ using SCIP linked to CPLEX as a branch-and-price framework. All additional solving techniques were implemented as modules for SCIP in the usual fashion.

For all computational results, models for Adaptive Flow Placement and Dynamic Network Design have been compared with a straight-forward implementation that solves the same problem, i.e. using the same routing formulation $\mathcal{R}$, however without pattern variables and the additional solving techniques.

All results were generated on a server with four Intel® Xeon® CPU E5-1620 processors with 3.60GHz and 16GB of RAM.

Table 6.4 outlines the characteristics of the randomly generated network topologies indicating the mean size of, number of traffic patterns in and number of commodities in the randomly generated fat-tree instances for each individual topology.

The test instances are randomly generated fat-tree instances with different properties. The set of instances describes a mix of sparse, as well as dense graphs and different amount of traffic patterns and bandwidth requirements. A table of statis-

Topology	$\lvert\mathcal{V}\rvert$	$\lvert\mathcal{E}\rvert$	$\lvert V\rvert$	$\lvert E\rvert$	# tp	# comm.
T1-*	48	190	379	190	10	29
T2-*	19	51	308	490	5	8
T3-*	64	173	1,386	2,739	5	20
T4-*	64	170	1,249	1,377	5	20
T5-*	53	188	7,133	31,293	20	20

Table 6.4: Different Randomly Generated Network Topologies

tics about the test instances is given in Table 6.4. For each type, five instances were considered, the statistics are mean values among each instance type. Instances of type T1 are connectivity tests, i.e. any assignment of routing paths yields a feasible solution. Instances of type T2 are rather small, however very dense networks. Instances of type T3 and T4 are very similar and differ mostly in the set of commodities which need to be routed. Instances in T3 have rather low bandwidth requirements, instances in T4 have low- as well as very high capacity requirements. Instance T5 is a medium-sized network that needs to ensure 20 traffic patterns, consisting of both, low and high traffic demands.

6.4.6.2 Computational Results

A brief summary of the results is given in Table 6.5. A column with the sum of running times and average optimality gap is given for both models. The advanced model yields stronger results in every instance. On average, the solution quality is increased by a factor of 99.4. With the advanced model, we were able to solve 9 out of 25 instances to optimality, hence the difference in solving time.

Name	Full		Advanced	
	Time	Gap	Time	Gap
T1	05:00	819.81%	02:10	1.21%
T2	05:00	611.80%	01:01	0.38%
T3	05:00	2,423.56%	02:54	0.57%
T4	05:00	113.18%	05:00	35.57%
T5	05:00	∞	05:00	12.15%
Total	25:00	992.09%	16:06	9.98%

Table 6.5: Simulation Evaluation and Comparison between the Full and Advanced Model

Six additional instances were solved to an optimality gap lower than 5%. The full formulation was not able to solve any instance to an optimality gap lower than 80%. On the big instances of type T5, not even the root LP relaxation was solved to optimality, due to the large number of variables. The worst optimality gap in the full formulation is 2695.91% in an instance of type T2. The advanced model is able to solve the same instance to optimality after 32 minutes, yielding both, better primal and dual bounds. The worst optimality gap for the advanced model does not exceed 50%.

Table 6.5 depicts the testbed results with an experimental duration limited to one hour. Results using the standard formulation on the left and the advanced model on the right side. Time columns show the sum of solver times among the five instances in the format hh:mm. The gap indicates the mean optimality delta.

6.4.6.3 Evaluation and Summary

We have seen both a model for adaptive network design, as well as an optimization framework that can be used to guide any, under mild assumptions, MIP-based routing model to find optimal solutions with respect to minimizing the total weighted operational cost arising from a number of traffic patterns. We chose fat-tree network topologies aligned to realistic telecommunication networks to validate our concepts. The results using a straight-forward approach have proven to be beyond any reasonable bounds, on bigger instances, the model was not even able to solve the root relaxation. The advanced MIP model however is able to solve the presented randomly generated test instances either to optimality or to prove optimality gaps that were lower than 10% on average. In addition to theoretical results, we have outlined how both modules can, independently of each other, be used in telecommunication networks.

6.5 Discussion and Comparison with other Solutions

This section discusses the individual characteristics of related solutions. Each of the related solutions is briefly described and differences as well as similarities are discussed.

6.5.1 Academic Concepts on QoS Control

Fu et al. described in [174] an approach for efficient network utilization and QoS improvement. Three optimization concepts have been combined, which include Traffic Management, Frame Filtering and Path Selection. In comparison with the approach taken in this thesis, Fu et al. assume an unlimited data rate within the core network, and focus only on the access network for the path selection. Costs for link or network nodes as well as user demanded QoS requests in form of service data flow prioritization have not been taken into account in this solution.

6.5.2 OpenDaylight Project

OpenDaylight [175] defines itself as a community-led, open, industry-supported framework, for accelerating adoption of, fostering new innovation in, reducing risk and creating a more transparent approach to Software-Defined Networking.

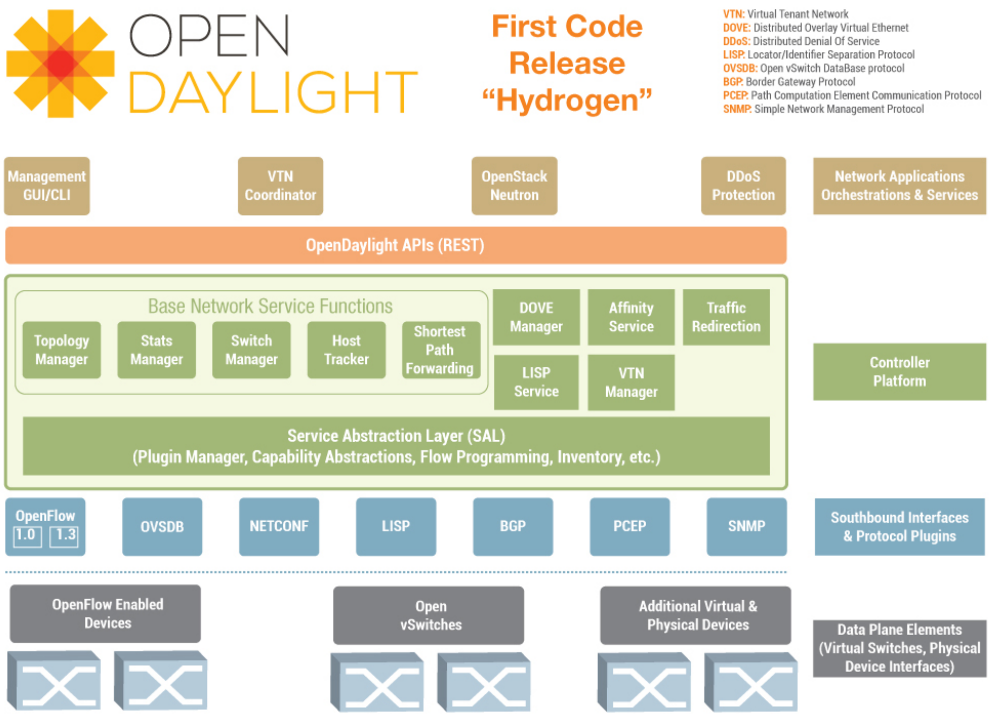

Figure 6.16: OpenDaylight Architecture [175]

A technical view on OpenDaylight presents three functional layers and (at least) two reference points as depicted in the official architecture Figure 6.16. The presented model of OpenDaylight, as initially presented in 2013, is related to the initial concept and implementation of this thesis presented and validated already in 2010 [91, 92] and 2011 [37] respectively.

A 'Network Applications Orchestration and Services' layer interfaces 'Data Plane Elements' within the OpenDaylight architecture through a 'Controller Platform' layer in between them. The centralized 'Controller Platform' connects to the lower 'Data Plane Elements' layer over 'Southbound Interfaces and Protocol Plugins, which is in line with the Adapter concept of GARC presented in 4.6.4.

The concept and implementation of OpenDaylight does not include any optimization nor Cross Layer aspects. In contrast to GARC, OpenDaylight only supports base network service functions for topology management, statistics shortest path forwarding and switch management.

The lack of OpenFlow version 1.4.0 support limits the features of OpenDaylight further on, in comparison to the approach presented in this thesis.

In addition, the network support of OpenDaylight is limited to SDN solutions, whereas GARC provides a generic support for heterogeneous network technologies.

6.5.3 Commercial Product Comparison

This subsection presents and compares related commercial products and solutions with GARC. During the time this thesis was being validated, it turned out that commercial products are rare in this field and that the ones available are limited to black box tests or functional comparisons.

The Active Resource Manager (ARM) [176] (released in August 2013) product of Active Broadband Networks provides related concepts in comparison to GARC. The core functions provided by ARM are designed to deliver dynamic managed broadband services, Network telemetry data collection and mediation, Big Data storage, Subscriber service management applications, Integration policy control functions. An Internet Statistics System (ISS) exposes IP detail records, which are the basis for highly accurate per subscriber Internet usage and network utilization information computation. External factors such as Subscriber Bandwidth Consumption, Network interface Utilization, Network Topology and Modem Status & Diagnostics are adapted into the policy decision process. With ARM, peak demand bandwidth consumption by service tier and management of 'Top Talker' during periods of network congestion can be controlled. In contrast to GARC, the ARM product operates only with PacketCable 2.0 Policy Control for IMS services. GARC in turn is designed as a generic Cross Layer Optimization function, which operates with OpenFlow, IMS and EPC networks, but is extensible through various adapters. User demanded QoS and fine granular QoS control per individual service are not taken into consideration in ARM either.

6.5.4 YoMo: A YouTube Application Comfort Monitoring Tool

YoMo [177] (or AquareYoum) measures video QoE through monitoring the amount of playtime pre-buffered by a YouTube [178] video and is thereby able to predict an imminent stalling of the video. The YoMo tool has been integrated into Mozilla Firefox as an add-on and extracts information out of the browser for further usage. The addon itself signals resource requirements into lower layer of an IEEE 802.11 based mesh testbed or data center while assuming redundant links. The goal of YoMo is to improve application-aware resource management by identifying bottlenecks within the network and to apply re-routing accordingly.

The web browser tool is limited to client based monitoring and YouTube services only. No prioritization and only re-routing in the network is taken as mitigation strategy into consideration. No dynamic QoS negotiation mechanisms are proposed nor user profile, authentication, authorization taken into consideration. The approach is limited to redundant backbones links without covering access- and core networks, which are the bottlenecks in today's networks.

6.5.5 Application-Based Network Operations (ABNO)

The Internet Draft (I-D) on ABNO [179] describes an architectural approach to introducing a new network control component for (G)MPLS networks. Some pasrt of the work share related concepts and ideas which allows the comparison in the following.

A Path Computation Element (PCE) [RFC4655] as a core part of the ABNO architecture is intended, but it is limited only to GMPLS and MPLS networks. The main idea of ABNN is to introduce novel network functions, which control resources in the network. Network elements are enabled to make path computation requests to a PCE using the PCE protocol (PCEP). This approach and the communication among architecture elements is not regarded as secure and efficient. No authentication or authorization is performed before executing the request. No user profile is evaluated before actually enforcing network policies. The path computation element does not differentiate between smaller and larger service data flows, which increases the potential for network state oscillation in case of multiple quick changes in the network. Functional elements have been defined but no reference points have been outlined and specified at the time this thesis was written. The ABNO is presented as initial draft; no implementation or validation is available. The usability is therefore difficult to determine and is left out of this analysis. Neither concepts for Dynamic Traffic Engineering nor Adaptive Network Management have been considered.

6.5.6 Summary and Comparison of Related Solutions

This subsection compares the contribution of this thesis with other approaches and solutions within a taxonomy. An evaluation reviews characteristics derived from the requirement analysis in 3.4 against the presented work.

During the preparation of the thesis, other approaches with related concepts have been published and released. Table 6.6 highlights the characteristics of those approaches, by comparing them against the initial requirements and GARC.

At the time this thesis was written, no approach has been identified besides GARC that covers most of the requirements mentioned in the previous Section 3.

User demanded QoS resource requests are not supported by any other identified solution.

The evaluation proves the richness of features provided through GARC in comparison to the other approaches.

Most of the identified requirements have been met by GARC.

It has been established that the scalability of GARC can be enhanced through further developments by integrating a horizontal interface for state synchronization between instances of GARC.

In comparison to the other solutions, GARC covers most of the requirements and is available as concept as well as implementation. No comparison with regard to the system performance could be created due to the lack of available implementations on the market.

Criteria	YoMo	OpenDaylight	ABNO	GARC
Modifications required?	Browser Plugin required	Specific SDN components required	Yes	Optional
User Demanded QoS Requests	Not supported	Not intended	Not intended	Realized
Flexible Application Support	No, limitation to YouTube	Conceptually possible but not existing	Not supported	Realized
Dynamic Traffic Engineering	Not supported	Not supported	Not supported	Realized
Adaptive Network Management	Not supported	Not supported	Part of concept	Realized
Topology Consideration	Limited	Conceptually	Yes	Intensively
Cost Efficiency/Optimization	Not supported	Not supported	Not supported	Supported
Heterogeneous Network Support	No, limitation to OTT Internet	Limited to SDNs	Supported	Supported
Network Abstraction Considered	No	Limited to SDNs	Not supported	Widely supported
Context Information	Medium	Not considered	Not considered	Supported and extensible
Openness and Expandability	Limited to FireFox	Open	Limited	Open
Device Capabilities	Not supported	Not supported	Not supported	Supported
Self Adaptation	Supported	Not supported	Not supported	Self-X algorithms included
Scalability	Transparent to the user	/	Not considered	Included in the concept
Usability	Simplified UE interaction	/		Simplified user interaction
Availability	Binaries	Source Code	Concept	Source Code
Evaluation	+	0	0	+++

Table 6.6: Comparison of Related QoS Control Approaches and Solutions NGN and FI

6.6 Summary

The Cross Layer Optimization function GARC has been validated within this chapter.

An extensive validation of GARC as part and in the scope of international ICT projects has been validated in 6.2. Both academic (GLab DEEP, FISTAR and NUBOMEDIA) and industry relevant projects (OpenEPC, OpenSDNCore and FOKUS Broker) include concepts and/or implementations of the Cross Layer Optimization function GARC. In addition, the requirements of the previous chapters have been compared against existing academic and industry solutions. Furthermore the delta between State of the Art and the thesis contributions has been outlined within a taxonomy in 6.3.

An extensive validation has proven the correctness of the concepts and implementations as well as the richness of features of GARC. Therefore various fixed and mobile transport networks (3GPP LTE, IEEE 802.11e, SDN/OpenFlow) have been evaluated in different testbeds. The dynamic Network Design and adaptive Traffic Engineering algorithm validation has been outlined separately under [146, 42, 145] extensively.

Related work has been improved and developed during the time this thesis was written in the form of commercial products and academic research. The subsection 6.5 first presents the characteristics of the related approaches and finally compares and evaluates those against GARC in a summary.

The following Chapter 7 summarizes the thesis in its contributions and impact.

Chapter 7

Thesis Conclusion

This *Summary* recapitulates the major findings of all previous sections and validates the initial research questions of Chapter 1.

7.1 Summary

Telecommunication network architectures move towards an All-IP data network environment, in which signaling, voice and other data are similarly transported as Internet Protocol packets. New requirements, challenges and opportunities are bound to this transition and influence telecommunication architectures. In this time in which the Internet in general and telecommunication networks in particular have entered critical infrastructures and systems, it is of high importance to guarantee an efficient and flexible data transport. A certain level of QoS for critical services is crucial even during overload situations in the access and core network as these are the bottlenecks in the network. However, the current telecommunication architecture is rigid and static, which offers very limited flexibility and adaptability.

Several concepts for clean slate as well as evolutionary approaches have been proposed and defined in order to cope with these new challenges and requirements. These ideas, concepts, standards, publications and products have been analyzed, compared and evaluated in the theoretical part of this thesis in Chapter 2 and Chapter 3. One of these approaches is the Cross Layer Optimization paradigm, further introduced and explained in Chapter 4. This concept omits the strict separation and isolation for the Application-, Control- and Network-Layer as it enables interaction and fosters Cross Layer Optimization among them. One indicator underlying this trend is the programmability of network functions, which emerges clearly during the telecommunication network evolution towards the future tactile Internet. The concept is regarded as one solution for future tactile mobile core networks. However, no standardized approach for Cross Layer signaling nor optimizations in between the individual layers had been standardized when this thesis was written.

The research question is formulated as 'Is the Cross Layer Optimization paradigm applicable to Fixed and Mobile Broadband Telecommunication Networks and Beyond?', which is answered with a clear 'Yes, the Cross Layer Optimization paradigm is applicable to Fixed and Mobile telecommunication networks andbrings added value'. The main objective of this thesis is the design (Chapter 4), implementation (Chapter 5) and evaluation (Chapter 6) of a Cross Layer Optimization concept for telecommunication networks. A major emphasis is given to the definition of a theoretical model and its practical realization through the implementation of a Cross Layer network resource optimization system for telecommunication systems.

The secondary key research questions in Chapter 1 have been answered, too. The Cross Layer Optimization paradigm can be applied on telecommunication networks, which has been presented and validated exemplary through the Generic-Adaptive-Resource-Control (GARC) function. New arising requirements for current and future telecommunication in terms of QoS support have been analyzed from various stake-holder perspectives. An extensive State of the Art analysis presented related work on service control, QoS management in NGN's and more. A gap analysis identified in section 2 the required functionalities that could not be covered through existing solutions. Finally, the evaluation of the new Cross Layer Optimization concept is viable and is a candidate to bring added value to the value chain of network operator and service provider.

The thesis and its contributions have been summarized fourfold:

- First, a review of related work, a requirement analysis and a gap analysis have been performed.

- Second, challenges, opportunities and design aspects for specifying an optimization model between application and network layer have been formulated and discussed.

- Third, a conceptual model - Generic Adaptive Resource Control (GARC) - has been specified and its prototypical implementation has been realized.

- Fourth, the theoretical and practical thesis contributions have been validated and evaluated.

Figure 7.1 illustrates parts of GARC, which have been reused in various ICT projects, student theses or student projects.

Source code, concepts and ideas of GARC have been transitively transported over various projects. Examples include Cross Layer Optimization and Application Awareness (AAW), which has been realized in the FhG Broker project and has evolved in some aspects into the BMBF G-Lab DEEP project. Other examples include the application of the SDN concept on the 3GPP EPC architecture for realizing Cross Layer Optimizations over the SDN Northbound Interface. The SDN

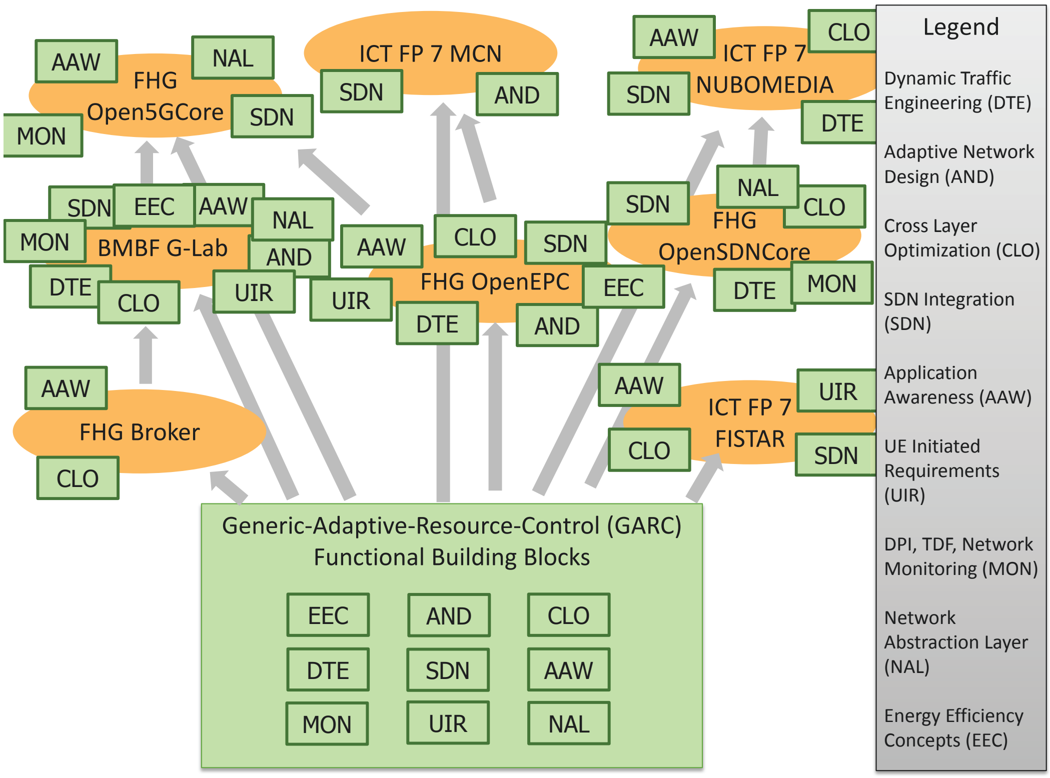

Figure 7.1: Flexibility of GARC and Reuse of Functionalities

enabled EPC is one of the key building blocks for the ICT project MobileCloud-Networking and also influences the 5G activities at Fraunhofer FOKUS and TU Berlin.

7.2 Evaluating the Research Hypothesis and Question

This section critically reviews and reflects on the initial Research Hypothesis and Questions presented in Section 1.4. A short reflection on individual thesis' chapters and sections is given.

> ***'Is the Cross Layer Optimization paradigm applicable to Fixed and Mobile Broadband Telecommunication Networks and Beyond?'***

This thesis has evaluated and proved the applicability of the Cross Layer Optimization paradigm in Fixed and Mobile telecommunication networks. A strong focus within the telecommunication networks has been put on the 3GPP network architectures, in which Cross Layer Optimizations have been applied on the Evolved Packet Core and IP Multimedia Subsystem.

The trend for Cross Layer approaches in telecommunication networks has been fostered through virtualization.

Furthermore, virtualization in telecommunication networks - namely SDN and NFV - have been investigated extensively, studied and analyzed as part of this thesis.

Today's static Next Generation Mobile Network architecture is challenged by several limitations in regard to the performance and flexibility. Virtualization concepts in general and Software Defined Networks (SDN) as well as Network Function Virtualization (NFV) in particular are considered as new opportunities for creating a novel scalable, elastic and demand-oriented telecommunication network. Decoupling the hardware from software within network functions and thus enabling a dynamic Virtual Network Function life cycle management will open up new business models for network operators as well as service providers, and addresses energy efficient networking at the same time.

Cross Layer Optimizations concepts are directly involved and have been applied in these aspects:

- SDN gateway split which is considered to improve the current 3GPP EPC architecture in terms of flexibility, scalability and controllability.
- User initiated QoS which enables new business models for QoS on demand and selected traffic prioritization.
- PCRF and ANDSF enhancements beyond the standard increasing the QoS decision process by including additional network internal parameters.
- QoS Supported IEEE 802.11e as a solution for enhancing QoS after data traffic offloading.
- Cross Layer improvements for OpenFlow covering the two aspects of 1) QoS in the OpenFlow network and 2) a telecommunication specific northbound interface.
- Cross Layer improvements for Network Management and Traffic Engineering.

Answers to the Secondary Research Questions

The secondary research questions, derived as aspects from the main research question, are:

> ***'Q1: What are the existing service control functions, protocols and solutions in mobile telecommunication networks?'***

The research hypothesis and question Q1 have been covered extensively in Chapter 1 (Introduction), Chapter 2 (Related Work) and Chapter 3 (Requirement Analysis and Engineering).

The main contributions of this thesis on Q1 are:

- Five horizontal domains for QoS service control mechanisms involved in IP data transport have been identified and analyzed: (1) user equipment, (2) access-, (3) core- and (4) backbone-network towards the (5) service or application.
- In a second dimension the network has been sliced conceptually into three parts (1) network, (2) control/mediation and (3) application layer.
- In a third dimension approaches and solutions have been aggregated into the four main fields of: academic work, industry products, standards and international ICT projects.
- The Cross Layer concept in this picture converges control mechanisms of all three dimensions and layers, which has been summarized within a taxonomy in Table 2.2.
- Book chapters [32, 33, 34, 180], journal papers [35, 36] and conference papers [42, 144, 38] have been generated out of the presented work.

> ***'Q2: What are the key design objectives and features for a Cross Layer optimization conceptual model and its specification?'***

The research hypothesis and question Q2 have been covered extensively in Cross Layer Optimization Concept and Specificationin Chapter 4 and Cross Layer System Architecture Model Implementation in Chapter 5. The main contributions of this thesis on Q2 are:

- The formulation of key design principles for realizing this thesis in Section 4.2.
- A generalized Cross Layer optimization concept designed in Section 4.2.1.
- A High Level Cross Layer Optimization Function Architecture Model specified in Section 4.4.
- Definition of a Core Cross Layer Optimization Functional Element Specification in Section 4.5.
- Cross Layer Optimization Architecture Reference Point Specification in Section 4.6.
- Cross Layer System Interaction Model presented in Section 4.7.
- Architecture Model and High Level Function Implementation in Section 5.1.
- Reference Points and Information Flows in Section 5.2.
- Book chapters [32, 33] and conference papers [145, 42, 144] have been generated out of the presented work.

> ***'Q3: What are the benefits and limitations of applying the Cross Layer Optimization paradigm applicable to mobile telecommunication networks?'***

The research hypothesis and question Q3 have been covered extensively in Chapter 6 of Validation and Evaluation as well as Chapter 7 entitled Conclusion. The main contributions of this thesis on Q3 are:

- The thesis compares today's approaches against the model presented here, its specification and implementation of the Cross Layer optimization concept in Chapter 6.
- Thesis influences on Fraunhofer FOKUS toolkits: OpenEPC, OpenSDNCore and Open5GCore projects.
- Thesis influences on international ICT projects: G-Lab DEEP, MCN, Nubomedia, FISTAR.
- Benefits and limitations have been discussed in publications as books, journals and conference papers. MSc and BSc theses and AV student projects have been formed out of the scope of the thesis.

7.3 Dissemination and Impact of this Thesis

This thesis work has been performed in collaboration with the Chair 'Architekturen der Vermittlungsknoten (AV)' [181] of Technical University Berlin and the Competence Center Next Generation Network Infrastructures (NGNI)' [182] Fraunhofer Institute FOKUS for applied science. The criteria for measuring the success and impact of this thesis have been evaluated in two parts. The first part is academic and the second is industry driven.

The academic part includes international ICT projects and proposals, workshop presentations, publications and university obligations, which relate to this thesis topic. The industry related part includes aspects like industry driven research projects and the licensed software toolkits by Fraunhofer FOKUS.

7.3.1 Academic Impact of the Author's Work

The academic impact is evaluated by publications and talks at international first class ITG, ACM and IEEE conferences, workshop and lectures at the Technical University for the two Chairs 'Architekturen der Vermittlungsknoten (AV)' and 'Offene Kommunikationssysteme (OKS)'.

The publication track of the author includes 26 publications for the time between 2009 and 2013.

- 4 book chapters

- 2 journal papers
- 20 IEEE or ACM conference publications

The most important publications of the author are:

- (Book chapter) J. Mueller, T. Magedanz, 'Der Evolved Packet Core', Handbuch der Telekommunikation [34]
- (Book chapter) T. Magedanz, J. Mueller, 'Introduction of the Evolved Packet Core', A Guide to the Wireless Engineering Body of Knowledge [180]
- (IEEE publication) J. Mueller, A. Wierz, T. Magedanz, 'Scalable On-Demand Network Management Module for Software Defined Telecommunication Networks', IEEE SDN4FNS 2013 [145]
- (IEEE publication) T. Mueller, T. Magedanz, M. Corici, D. Vingarzan, 'UE & Network Initiated QoS Reservation in NGN and Beyond', IEEE Network of the Future (NOF) 2011 [38]
- (ETSI publication) J. Mueller, V. Vlad, 'SDN and Openflow Impacts on EPC Evolution', ETSI Future Networks Workshop, Sophia Antipolis, France, April 9-11, 2013, http://www.etsi.org/news-events/events/617-2013-future-networks [144]
- (ITG publication) J. Mueller, T. Magedanz, 'Generic-Adaptive-Resource-Control (GARC) in Next-Generation-Networks and the Future Internet', Demonstration, 12th Würzburg Workshop on IP: ITG Workshop "Visions of Future Generation Networks“ (EuroView2012), Würzburg, Germany, July 23rd - July 24th 2012
- (Book chapter) M. Corici, J. Mueller, D. Vingarzan, T. Magedanz, LNCS book, Chapter 2. 'Technical assets I - Network and control platforms' [32]
- (Book chapter) N. Blum, J. Mueller, F. Schreiner, T. Magedanz, LNCS book, Chapter 3. 'Technical assets II - Telco applications, APIs, SDPs' [33]
- (IEEE publication) T.-H. Truong, N. H. Thanh, N. T. Hung, J. Mueller, T. Magedanz, 'QoE-aware Resource Provisioning and Adaptation in IMS-based IPTV Using OpenFlow' [41]
- (IEEE publication) L. Lange, T. Magedanz, J. Mueller, D. Nehls, D. Vingarzan. 'Evolutionary Future Internet Service Platforms Enabling Seamless Cross Layer Interoperability' [183]
- (Whitepaper) A. Manzalini, D. Soldani, A. Galis, J. Mueller and et al., 'Software-Defined Networks for Future Networks and Services', White Paper based on the IEEE Workshop SDN4FNS [143]

- (Whitepaper) T. Magedanz, M. Corici, J. Mueller, A. Weber and C. Cillis, 'COMPREHENSIVE NFV/SDN SOLUTIONS are already available - Benefit from Future-Proof Solutions Today' [184]

During the creation of this thesis, the author has given various talks at international industry conferences and academic workshops. 14 industry talks (e.g Informa, Layer123, Bitkom, Marcus Evans), 11 academic conference presentations (ETSI, KUVS, GI/ITG, ngnlab.eu) and nine IEEE conference tutorials have been presented in the time between 2009 and 2013. The most relevant talks are the following:

- J. Mueller, 'Flexible Quality-of-Service control in Next-Generation mobile broadband networks using OpenFlow', Layer123, SDN & OPENFLOW WORLD CONGRESS, Darmstadt, Germany, October 22-24th, 2012, www.layer123.com/sdn
- J. Mueller, 'Mobile Cloud – Combining EPC, SDN and NFV', Beitrag zum 44. Fachgruppenworkshop on Mobile Network (Function) Virtualization and Software Defined Networks of ITG Informationstechnische Gesellschaft im VDE FG 5.2.4 'Mobility in IP-based Networks', Munich, Germany, 15.11.2013
- J. Mueller, 'SDN / Openflow Impacts on EPC Evolution', 8th Workshop (Fachgespraech) on Next Generation Service Delivery Platforms, 'Competitive Service Delivery Infrastructures', of the GI/ITG specialist group on Communications and Distributed Systems "Kommunikation und Verteilte Systeme (KuVS)", Vodafone-Schulungszentrum, Königswinter, Germany, 8th Meeting on April 17, 2013, http://www.kuvs-ngsdp.org
- J. Mueller, T. Magedanz, 'Applying Virtualization Principles on Telecommunication Next Generation Mobile Broadband Networks', Informa SDN World, "Defining the Service Provider Business Case and Developing Carrier Class SDN" Barcelona, Spain, June 11-13, 2013, http://sdnworldevent.com/

The thesis author has organized and chaired two workshops: ONIT and FUSECO@KiVS. The 3rd International IEEE Workshop on Open NGN and IMS Testbeds (ONIT 2011) @ COMPSAC 2011 Next Generation Network Evolution Towards the Future Internet, July 18-22nd, 2011, Munich, Germany. All relevant aspects from workshop proposal formulation, over creation and distribution of the Call for Papers (CfP) to the organization of the EDAS reviewing system have been organized by the thesis author.

Also the organization committee and workshop chair of FUSECO@KiVS (Kommunikation in Verteilten Systemen) 2011 was the responsibility of the thesis author.

In addition, several Technical Program Committee (TPC) memberships have been taken on.

- 1ST IEEE / IFIP International Workshop on SDN Management and Orchestration, http://clayfour.ee.ucl.ac.uk/sdnmo2014/

- IEEE 2013 Software Defined Networks for Future Networks and Services (SDN4FNS), http://sites.ieee.org/sdn4fns/
- IEEE Communications Magazine Feature Topic on '5G Networks: End-to-end Architecture and Infrastructure', http://www.comsoc.org
- IEEE 4th International Workshop on Context-aware QoS Provisioning and Management for Emerging Networks, Applications and Services, co-located with IEEE 23rd International Conference on Computer Communications and Networks (ICCCN), http://contextqos.org/
- The Third International Conference on Advances in Future Internet, AFIN 2011, August 21-27, 2011, http://www.iaria.org/conferences2011

The thesis author is a frequent assistant lecturer at the Technical University Berlin in the courses 'Next-Generation-Network-Technologies (NGN)', 'Grundlagen Offener Kommunikationssysteme (GOKS)' and 'Future-Internet-Technologies (FIT)'. He is supervisor of the practical student project course 'NGN and FI Projects' of Technical University Berlin, Germany chair Next Generation Networks (NGN/AV) since summer term 2010.

Julius Mueller is member of 'Gesellschaft der Informatik (GI)' and 'Institute of Electrical and Electronics Engineers (IEEE)'.

The following lectures, projects and seminars have been given by the author at the Technical University for the Chair 'Architekturen der Vermittlungsknoten (AV)'.

- (Since summer term 2009) lecturer in the AV course 'Next Generation Networks (NGN)'
- (Since summer term 2009) lecturer in the AV course 'Future Internet Technologies (FIT)'
- (Since summer term 2009) lecturer in the OKS course 'Grundlagen Offener Kommunikationssysteme (GOKS)'
- (Since summer term 2009) supervision of the AV university student projects namely 'AV Projects'

7.3.2 Industry Impact of the Author's Work

The licensed software toolkits of Fraunhofer FOKUS namely OpenEPC Rel.5 [167]/6.2.4 and OpenSDNCore [170]/6.2.5 contain concepts and developments of the thesis work.

The following table 7.1 maps the thesis' contributions to the Fraunhofer FOKUS toolkits.

The concepts of GARC enabling data traffic forwarding parallelization, data traffic steering, backhaul level offloading for massive broadband communication between end-users and data centers and between data centers in the FOKUS toolkits.

Aspect	**Toolkit(s)**	**Description**
Network-aware Applications	OpenEPC, OpenSDNCore, Broker	3GPP EPC control and data plane split further on in the packet core gateways. Network-aware services and core network enhancements for service-awareness for networks.
Enhanced PCC Control	OpenEPC, Broker	Using the flexibility of SDN to enhance the 3GPP PCC functionalities.
Traffic Engineering and Network Management	OpenEPC, OpenSDNCore	Flexible Traffic Management including Adaptive Flow Placement and Elastic Network Design. Flexible access- and core network topology management. Self-Organizing-Network (SON) concepts and enabling smart resource control.
Application requirement signaling	OpenEPC, OpenSDNCore, Broker	Enabling efficient backhauling considering forwarding consistency, fast routing information convergence, reliable data forwarding according to transport and core network requirements.

Table 7.1: Mapping Thesis Contribution on Fraunhofer FOKUS Toolkits

Both projects include the Cross Layer OpenFlow implementation of the controller, switch and protocol in version 1.4.0. As part of the functional split of the gateways, the OpenEPC includes SDN concepts in the Serving Gateway (SGW) and Packet Data Network Gateway (PGW). As part of the deployed telco environments, the Orchestrator functionality of the OpenSDNCore deploys the OpenFlow enabled OpenEPC Rel.5.

Julius Mueller is an active member in ETSI IMS Network Testing (INT). Within INT he has been selected as rapporteur for the work item on IMS & EPC interoperability on Update of IMS NNI Test Specifications for 3GPP R9 RCS 3.0 and IMS & EPC within STF435. Next to IMS and EPC interoperability, he is contributing to investigating, testing and interoperability tests for telco and SDN/NFV within the ETSI ISG INT.

7.4 Outlook and Future Work

This section discusses further developments of GARC and the realization of concepts and implementation aspects of GARC within international ICT projects as well as standardization activities within ETSI.

7.4.1 Future Work Directions

A new trend can be recognized, in which software is entering more and more parts of the network. The two concepts of SDN and NFV dissolve the fixed telecommunication network elements. Flexibility and optimization can be seen as two of the major requirements of the next future tactile Internet expected in 2020. In order to achieve these requirements, Cross Layer approaches are part of the discussion. Ideas and concepts of GARC and the Cross Layer optimization model might become crucial aspects of this new system.

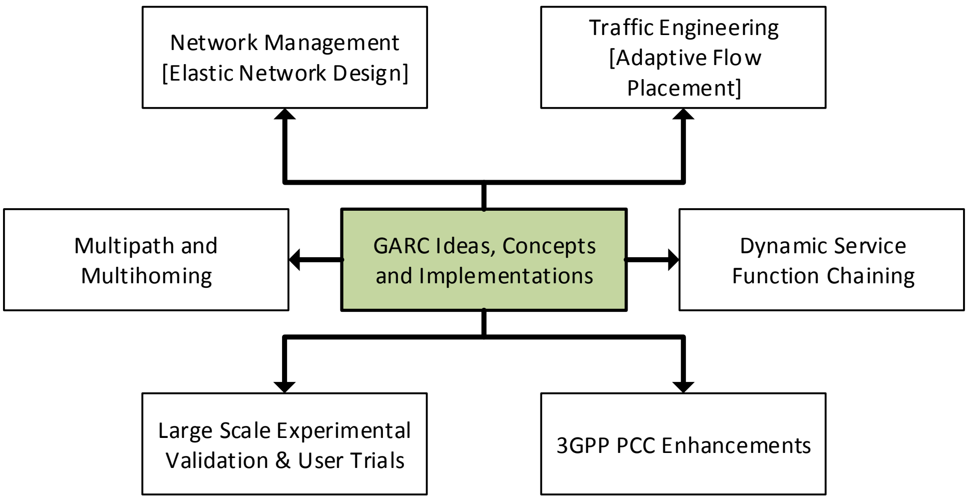

Figure 7.2: Related Research Trends and Future Work of this Thesis

Figure 7.2 depicts the main potential future work directions of this thesis work, which are outlined briefly.

In summary, OpenFlow is used in these research domains:

Telco Network Virtualization Applying cloud principals to telco network components requires additional operation and management complexity but also a higher level of resource utilization and cost saving in parallel. Advantages and disadvantages of the cloudified new telco environment have to be compared and evaluated. Application and network need to be aligned, controlled and orchestrated. The ongoing ETSI NFV Management and Orchestration Architecture (MANO) standardization addresses these aspects and challenges. Virtual or non-virtual network functions in the network will be controlled through NFV Orchestrator (NFVO), VNF Manager (VNFM) and Virtual Infrastructure Manager (VIM).

Traffic Engineering An algorithm for on-demand and context based traffic engineering as part of GARC has been presented within this thesis.

Other algorithms for optimal service data flow placement will be evaluated as part of the future work, based on different metrics. These include but are not limited to cost, efficiency, application type and network technology.

Network Management The demand-driven enabling or disabling of virtual or physical network functions still has open questions and unsolved challenges. The NP-hard mathematical network optimization problem is not suitable for large scale networks.

Another dimension of the complexity is introduced through multihoming and multipath. Multipath TPC (MPTCP) is regarded as one efficient approach for improving the connectivity between two points. Mobile devices are therefore enabled to combine resources of different access network technologies in parallel on different paths. MPTCP improves the total throughput and enhances reliability of the connection, but consumes more power and costs at the same time. The routing of each individual path increases the network management process even when taking different application requirements into account.

3GPP PCC Enhancements Further extensions to the current 3GPP Policy Charging and Control architecture and functionalities for virtualized environments are followed as part of the future work. The signaling between PCC-related components of the telco network and SDN/NFV related components is not yet standardized. Candidate protocols are Diameter or JSON RPC for realizing the SDN Northbound Interface (NBI) for the telco domain. The PCC and NBI modifications might influence the virtualized telco networks on a mid to long term perspective and will enable new business models through the integration of new control mechanisms.

Dynamic Service Function Chaining The combination of the previous aspects telco network virtualization, traffic engineering and network management enables dynamic Service Function Chaining (SFC). Service chaining refers to the ability to combine services dynamically through an external control and modification of the routing path. Cost intensive VNF such as deep packet inspection, de-/encryption or virus scanner can be added or removed to individual data path dynamically. Network-aware service and service-aware networks are the basis for enabling this feature efficiently. Cross Layer Optimization aspects are candidate solutions for bridging the gap between application and network to finally realizing dynamic SFC.

Optimized Service Function Placement Aligned with the dynamic SFC optimized Service Function Placement (SFP) will also change the way services are provisioned. The question of where to position or when to migrate virtual network components needs to be answered with regard to the cloudification of networks.

The service life cycle of VNF, starting with instantiation, through configuration and management, until disposal needs to be orchestrated and controlled.

The point in time for changing the life cycle or migrating VNF within a single or multiple geographically distributed data centers will be targeted as part of future work in the MobileCloud Networking and Nubomedia projects.

Green-ICT Aspects Power control with regard to green-networks is applicable to the concept of this thesis work, but is left for further discussions and future work.

Early research and development in the scope of 5G emerged at the time of writing the thesis. The overall tenor of position papers of vendors and operators includes the requirement of massively reducing energy consumption within the network.

Concepts and implementations of this thesis are applicable to the new mobile network generation 5G and will be further analyzed.

Large Scale Prototypical Validation The prototypical realization and experimental validation have been focusing on small testbeds due to complexity.

Large scale experiments are envisioned as part of testbeds e.g. the OFELIA project testbed.

Heterogeneous network environments including multiple domains consisting of various types of controller, switches and protocol versions are to be taken into account for future work.

Performance validations including a large number of simulated or emulated users each having a large amount of connections need to be investigated in order to validate scalability, reliability and availability.

7.4.2 Active contribution to Standardization Efforts

Two main standardization activities are followed within this thesis, which are further elaborated.

- ONF Northbound Interface (NBI)
- ETSI INT interoperability test

Firstly contributions to standardization efforts for the Northbound API (NBI, [142]) standardized by OpenNetworking-Foundation (ONF). The NBI standardization started in June 2013. According to the released charter [141] the goals also include Cross-Layer Optimization specific aspects. Cross Layer information exchange is targeted through exploiting protocol, vendor or media specific features to other protocol layers. Telecommunication specific reference points for mobility, QoS resource control, traffic engineering, network management, network based security and charging should be taken into account.

Secondly, continuing the active contribution within the ETSI SIG INT [185] to testing and interoperability for telecommunication and virtualization in particular SDN/NFV. The INT special interest group is extending the scope from IMS to any transport network including virtualized networks. According to the roadmap of INT, relevant technologies are investigated first, before specifying an interoperability test, which are finally validated as part of annual plugtests.

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List of Acronyms

2G	2nd Generation Wireless Telephone Technology (GSM)
3G	3rd Generation Mobile Telecommunications (UMTS, CDMA2000)
3GPP	3rd Generation Partnership Project
4G	4th Generation Mobile Telecommunications (LTE, WiMAX)
5G	5th Generation Mobile Telecommunications
AAA	Authentication, Authorization and Accounting
ADQ	Application Driven QoS
ALTO	Application Layer Traffic Optimization
ANDSF	Access Network Discovery and Selection Function
ANI	Application to Network Interface
API	Application Programming Interface
ARPU	Average Revenue Per User
AVC	Advanced Video Coding
BBERF	Bearer Binding and Event Reporting Function
BMBF	Bundesministerium für Bildung und Forschung
BRAS	Broadband Remote Access Server
CAPEX	Capital Expenditures
CDMA	Code Division Mutliple Access
CDMA2000	CDMA 2000
CDN	Content Delivery Networks
CE	Control Element
CINA	Collaboration Interface between Network and Applications
CLO	Cross Layer Optimization
CMTS	Cable Modem Termination System
CN	Core Network
COTS	Commodity Off The Shelf
CPE	Customer Premises Equipment
CRLF	Carrier Return Line Feed
CSCF	Call Session Control Function
CW	Contention Window
DCP	DiffServ Code Point
DEA	Diameter Edge Agent
DHT	Distributed Hash Table
DiffServ	Differentiated Services
DOCSIS	Data Over Cable Service Interface Specification
DRA	Diameter Routing Agent
DSCP	Differentiated Services Code Point
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
E2E	End-to-End

EPC	Evolved Packet Core
ePDG	Evolved Packet Data Gateway
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
FE	Forwarding Element
FEC	Forwarding Error Correction
FI	Future Internet
FP7	7th Framework Programme
FS	Feasibility Study
GARC	Generic Adaptive Resource Control
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GSMA	GSM Association
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
HTTP	Hypertext Transfer Protocol
I2ND	Interface to Network and Devices
ICT	Information and Communication Technology
IETF	Internet Engineering Task Force
IMS	IP-Multimedia Subsystem
IntServ	Integrated Services
IP	Internet Protocol
IPTV	IP Television
ISO	International Standardization Organization
ISP	Internet Service Provider
ITU-T	ITU - Telecommunication Standardization Sector
ITU	International Telecommunication Union
JCP	Java Community Process
LDAP	Lightweight Directory Access Protocol
LTE	Long Term Evolution
MME	Mobility Management Entity
MOS	Mean Opinion Score
MTU	Maximum Transmission Unit
MVNO	Mobile Virtual Network Operator
NASS	Network Access Sub-system
NE	Network Entity
NETCONF	Network Configuration
NFV	Network Function Virtualization
NGN	Next Generation Network
NGN2FI	Next Generation Network to Future Internet
NP-hard	Non-deterministic Polynomial-time hard
OFC	OpenFlow Controller
OFP	OpenFlow Protocol

OFS	OpenFlow Switch
OMA	Open Mobile Alliance
ONF	Open Networking Foundation
OPEX	Operating Expenditure
OSA	Open Service Access
OSI	Open System Interconnection
OTT	Over-The-Top
P2P	Peer-to-Peer
PAM	PacketCable Application Manager
PCC	Policy and Charging Control
PCEF	Policy and Charging Enforcement Function
PCRF	Policy and Charging Rules Function
PDP	Packet Data Protocol
PEP	Policy Enforcement Point
PGW	Packet Data Network Gateway
PoC	Proof of Concept
PPPoE	PPP over Ethernet (PPPoE)
QCI	Quality of Service Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
RACS	Resource Admission Control System
RAT	Radio Access Technology
RCS	Rich Communication Suite
REST	Representational State Transfer
RFC	Request for Comments
RPC	Remote Procedure Call
RSVP	Resource Reservation Protocol
RTCP	Real-time Transport Control Protocol
RTP	Real-time Transport Protocol
SAE	System Architecture Evolution
SCM	Service Control Mechanism
SCTP	Stream Control Transmission Protocol
SDN	Software-Defined Networking
SDO	Standardization Organization
SDP	Session Description Protocol
SFC	Service Function Chaining
SGW	Serving Gateway
SIG	Special Interest Group
SIP	Session Initiation Protocol
SLA	Service Level Agreement
SMTP	Simple Mail Transfer Protocol
SNMP	Simple Network Management Protocol
TCP	Transmission Control Protocol
TDF	Traffic Detection Function

TISPAN	Telecommunications and Internet converged Services and Protocols for Advanced Networks
TMF	TeleManagement Forum
TSP	Telecommunication Service Provider
TUB	Technische Universität Berlin
UDP	User Datagram Protocol
UE	User Equipment/Endpoint
UMTS	Universal Mobile Telecommunications System
VAS	Value Added Service
VNF	Virtual Network Function
VoD	Video on Demand
VoIP	Voice over IP
WiMAX	Worldwide Interoperability for Microwave Access
XML	Extensible Markup Language

Appendix A

Thesis Glossary

The following terms and definitions have been used within this thesis.

Generic A characterization in object-oriented programming to abstract an entire group or class.

Adaptive The ability or behavior of a system to react on external influences.

Resource The term 'resource' is used in a general sense for any controllable object, which may be a network resource in form of bit rate, a network resource as gateway, an IP service, a bearer or a virtual or physical network (slice). *'Any set of physically or conceptually identifiable entities within a telecommunications network, the use of which can be unambiguously determined.'* [15] *'Something of value in a network infrastructure to which rules or policy criteria are first applied before access is granted.'* [82]

Control The ability to modify the behavior of a system from external or internal.

Cross Layer The scope of the term Cross Layer in this regard refers to two dimensions. The first dimension is vertical and includes the ISO/OSI layer. The second dimension is horizontal and includes the End-to-End view of a service data flow starting at the UE, traversing the access, core and backbone networks and terminating at the service.

QoS The collective effect of service performance which determine the degree of satisfaction of a user of the service.2101. The ITU-T Recommendation E.800 [15] provides the basic definition of Quality-of-Service (QoS) as follows: *'Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service.'*

QoE Quality-of-Experience is defined as a subjective measure of a customer's experiences. QoE is also defined as perceived QoS by the user.

QoS policy rule A QoS policy rule characterizing the level of QoS. A QoS policy rule is validated against QoS requests and either validated true or false.

Future Internet An academic view on the evolution or revolution of the current Internet distinguishes between the main pillars: a) Internet of Things, b) Internet of Services and Content and c) Network of the Future. This work focuses on c) Network of the Future with a strong accent on service control and network virtualization techniques.

QoS requirements An abstract of fine granular definition of demanded QoS parameter for a given service. Also referred to as QoS parameters.

QoS request An abstract of fine granular definition of demanded QoS signaled from inside or outside of the telecommunication system towards the Policy-Decision-Point in the network.

Capability Definition in [15] at 2307 by ITU-T: *'The ability of an item to meet a demand of a given size under given internal conditions'.*

Service-Data-Rate in a multimedia IP data connection consists out of window-size, resolution and frames-per-second.

Application parameter Application parameter formulated as QoS requirements stated in a QoS request as a list of codecs, list of supported bit rates, resolution, frame-rate for a given service data flow.

Network capabilities Network capabilities defined as a network priority level represented as a QoS-Class-Identifier (QCI) support.

Application to Network Interface ITU-T recommendation: *'Interface which provides a channel for interactions and exchanges between applications and NGN elements. The ANI offers capabilities and resources needed for realization of applications.'* [51]

The following terminology was published by 3GPP in [126] part 22 and are relevant definitions for the thesis.

Policy An ordered combination of policy rules that defines how to administer, manage, and control access to resources. Derived from RFC 3460 [214] and RFC 3198 [213]. 'The combination of rules and services where rules define the criteria for resource access and usage.' [82]

Policy Rule A combination of conditions and actions to be performed if the condition is true.

Policy Action Action (e.g. invocation of a function, script, code, workflow, etc) that is associated to a policy condition in a policy rule and that is executed when its associated policy condition results in "true" from the policy evaluation step.

Policy Condition A condition is a Boolean predicate that yields true or false.

Policy Evaluation The process of evaluating the policy conditions and executing the associated policy actions up to the point that the end of the policy is reached.

Policy Provisioning The act of describing, creating, updating, deleting, provisioning, and viewing policies. A meta-model or representation scheme may be used in this activity.

Resource Any component, function, or application that can receive and process requests.

Role A type of attribute that is used to select one or more policies for a set of entities and/or components from among a much larger set of available policies.

Appendix B

Author's Publications, Contributions to Standards and Presentations

B.1 Publications

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Appendix C

Annex

C.1 MIP-Solver Topology Representation

The representation of the network topology has been structured as followed. Physical and logical links (lines/line cards), QoS classes, weighted traffic pattern and end hosts have been defined.

```
#L <uint64 dpid> <uint16 treeLevel>
#P <uint64 dpid> <uint64 log dpid> <uint32 cost> <uint64 flags>
#E <uint64 u dpid> <uint6 4v dpid> <uint64 capacity>
#QOS <uint8 qos> <string description>
#QOS_POLICY <uint8 qos> <uint8 type> <uint64 flags>
#TP <uint32 tpId> <uint32 weight>
#TPC <uint32 tpId> <uint64 dpid source> <uint64 dpid dest> <uint8 qos> <uint64 bandwidth>
#H <uint64 dpid of entry point>
```

L refers to the logical node. The input parameter assume one line of L for each logical node.

One line of P for each physical line card. Attributes of this element are cost representative for each path e.g. 10, 50 or 100. Additional flags indicate the importance e.g. if this component has to be always on or can be disabled for network optimization. Also trusted and untrusted networks can be defined, in order to influence routing decisions accordingly.

One line of E for each physical line enriched with the attribute physical capacity.

One line of QOS to initialize each QoS class. Optional attributes are human readable descriptions.

One line of QOS_POLICY for each policy in the given class. Multiple QoS policies are allowed in the same network topology for different purposes.

One line of TP for each traffic scenario. One line of TPC for each commodity in traffic pattern id. Well known Traffic Pattern (TP) are assumed as given to optimize the network accordingly. Since TP occur regularly, those values can be derived out of common network monitoring systems.

One line of H for each host is representing and characterizing the end host.

C.2 Related Work on Scheduling Approaches

C.2.1 Best-Effort Scheduling

By default, the gateway receives the incoming packets and sends them right away, without changing their order. This mode is called best-effort delivery. The clients receive no guarantees about the quality of service that they get, the bandwidth, the delay, the drop rate is unspecified. To assure the QoS constraints, additional packet processing is required, e.g. packets reordering, traffic shaping or policing (dropping).

C.2.2 First-Come, First-Served

FCFS, or FIFO (First In, First Out), scheduling doesn't differ from the best-effort, and is used mostly to gather statistics. The packets are sent in the same order as they are received, and in the mean time reside in a "First In, First Out" buffer of a fixed size (in bytes or in packets). The packets, that don't fin in the queue, are discarded.

C.2.3 Disadvantages of Best-Effort Delivery

Best-effort scheduling may lead to a resource starvation, when some of the flows don't get some share of a bandwidth for a long time. Another unwanted situation is a case, when clients try to send more packets, than the destination network can accept, which may result in uncontrolled massive tail packet drop.

C.2.4 Round-Robin

Round-robin scheduling (RR) is used to prevent resource starvation. A separate queue is assigned for every data flow. The queues are processed in the repeated order, and every queue can send the packets during a limited amount of time, or a limited number of packets, or a limited number of bytes. If some queue dosn't have any packets, the scheduler proceeds to the next queue, so the resources of the link are not lost.

There are modifications of the RR scheduling. Weighted round robin (WRR) uses different limits for different flows, as if the flows had different weights. Usually the limits are set to $\frac{w}{mean\,packet\,size}$, where w is a constant. The disadvantage of this approach is that the mean size of a flow packet should be known in advance.

Another modification is deficit round robin (DRR), which can handle packets of various size better than WRR. Each flow queue has a deficit counter. Packets are served only if their size is smaller than the deficit counter of their queue. Each time a packet is sent, the counter is decreased by its length, and after every round it is increased by a constant quantum. If the queue is empty, the counter is reset.

C.2.5 Random Early Detection

Tail packet drop can lead to TCP global synchronization. To avoid tail packet drop, random early detection (RED) may be used. Every incoming packet can be dropped with some probability. The value of the probability of being dropped depends of the size of the queue; if the queue is empty, it's 0, if the queue is full, it's 1, and it grows as the length of the queue grows. RED is more fair to bursty traffic that use a lot of traffic for a short period of time. The probability of a packet to be dropped depends of the amount of data the flow sends.

Other modifications of RED are weighted RED (RED), RED with in and out (RIO), adaptive RED (ARED) and robust RED (RRED).

C.2.6 Token Bucket Filter

Token bucket filter (TBF) is a simple algorithm that allows to limit the rate of a data flow. Every flow has an associated counter (token counter), that is incremented with a constant rate. The tokens represent data units, normally bits or bytes, and the token rate is the goal rate of the flow. The value of the counter is limited from above. If the length of an incoming packet is smaller than the value of the counter, the length is subtracted from the counter, and the packet is passed. Otherwise, the packet is considered as non-conformant, and is dropped or queued until it will be conformant and can be sent. The limit of the counter determines the maximal burst of the flow. It should be bigger than the maximum possible packet size. The limit could be set to a bigger value for bursty protocols, for example email.

C.2.7 Hierarchical Schedulers

The schedulers described above treat all flows as of the same rank. In practical applications, it is often required to handle flows differently, depending on the source or destination host or network, port, protocol, or application family. Similar flows are grouped into classes (leaf classes). Classes can further be grouped into classes of the higher level; for example, they can correspond to separate clients, or separate departments of an organization. The top level contains one root class that covers all data flows. Each class imposes its own set of traffic constraints. The lower-level classes of the same sub-hierarchy use bandwidth provided by their parent class, and can borrow bandwidth from their sibling classes if the siblings don't use the whole bandwidth allocated to them.

Additionally, priorities may be assigned to the leaf classes. The classes with the highest priority are served first.

C.2.8 Class-Based Queueing

Every class gets its guaranteed assigned share of the overall bandwidth (in percent or in absolute units). The share of an intermediate class is the sum of the shares of its children, and the share of the root class is usually 100% (it can also be set to a lover value to emulate a narrower data link). If some flows don't use their whole allocated share, the rest is being distributed between the flows that request more bandwidth than it's guaranteed to them. The classes borrow the traffic from their siblings, in the order of priority.

C.2.9 Comparison

Criteria	FCFS	RR	RED	TBF	PRIO	CBQ	HTB
starvation avoiding	no	yes	no	yes	no	yes	yes
congestion avoiding	no	no	yes	no	no	yes	yes
priority	no	no	no	no	yes	yes	yes
guaranteed rate limit	no	no	no	no	no	yes	yes
max rate limit	no	no	no	yes	no	no	yes
hierarchical classes	no	no	no	no	no	yes	yes

Table C.1: Comparison of Scheduling Approaches

C.3 Selected Open Source Software and Development Tools

This section outlines the software tools, technologies and techniques, which have been applied, while developing the Generic Adaptive Resource Control functionality.

Mainly Open-Source software has been selected for realizing the prototypical implementation of the previous chapter 4. The following list gives an overview of the major - manly Open Source Software tools. In addition, this chapter motivates the selection and outlines the major benefits provided through the individual software tool.

Java EE 6 SDK The Open-Source and platform independent programming language ORACLE Java EE 6 SDK with JDK 7 U5 [198] supports the key requirements for realizing GARC. Java is efficient, stable and secure for realizing browser based web applications.

Java-Server-Pages (JSP) Java-Server-Pages (JSP) is a technology for supporting web developers in creating dynamic web pages using Hypertext-Markup-Language (HTML), Cascading Style Sheets (CSS) and Extensible Markup Language (XML). JSP is used in combination with a Webserver (e.g. Apache Tomcat) and optional data bases.

Apache Tomcat 7 Apache Tomcat 7 [197] is an open source software Java Servlet Container and implementation of JavaServer Pages technologies for building dynamic Web-Services. Apache Tomcat is available under Apache License version 2, platform independent, scalable and robust. A web.xml file includes a list of servlet which maps servlet-names to servlet-classes and define the selected parameter name, which in turn trigger a functionality within the servlet.

Eclipse IDE for Java EE Developers Eclipse is a multi-language Integrated Development Environment (IDE) supporting required plug-ins for version control (subversion), various web server (Apache Tomcat/JBOSS) and integrated build process support (maven). It supports multiple programming languages and enhances the programming through auto-competition, step-wise debugging, etc. Eclipse is available under the free software license Eclipse Public License (EPL), which allows the license receiver to use, modify, copy and distribute the work and modified versions of it. The current Eclipse version Juno (4.2) provides packages for Java EE Developers.

Subversion Subversion [201] is a free versioning tool for software development in a distributed team. A centralized code base is extended by individual contributers and changes are tracked for other collaborative partners. The Eclipse extension for Subversion namely Subversive [202] eases the management of source code and the contribution of new functionalities or code updates.

Maven Apache Maven is a software project management and comprehension tool, supporting continuous integration and effective dependency management [200]. An eclipse plug-in for Maven eases the dependency management further on. Maven introduces an additional pom.xml file into a software process, in which dependencies to internal or external libraries are listed and managed.

JUnit Testing Suite Software development processes consists of testing as fundamental design stage. The test driven development software JUnit version 4.11 [199] enables functional testing of complete software projects or individual selected components in various test cases. JUnit 4.11 is available under Common Public License - v 1.0 and offers a detailed documentation as well.

HighCharts JS The JavaScript charting library namely HighCharts JS [196] was selected for visualizing charts within web applications. HighCharts used by universities is free under the Creative Commons Attribution - Non commercial 3.0 License.

GStreamer GStreamer [204] is a platform independent library for constructing graphs of media-handling components. The GStreamer Open-Source multimedia framework supports multiple video codec and is available for unix and Windows at GStreamer Core version 0.11.92 currently.

Used Software Libraries in GARC			
Name	**Version**	**Used in Module**	**License**
Java	1.7	GARC Framework	Fraunhofer License
JSON-Lib	2.4	GARC Monitoring Interface, Application interface, OpenFlow Controller Interface	The Apache Software License, Version 2.0
Jsch	0.1.45	OpenFlow Switch Interface	BSD-Style (http://www.jcraft.com/jsch/)
highchart.js	2.4	Monitoring GUI	Creative Commons Attribution-Non Commercial 3.0 License
JQuery	1.7.2	Monitoring GUI	MIT
Apache Tomcat	2.7	Monitoring	The Apache Software License, Version 2.0

Table C.2: Overview of the Used Software Libraries in GARC

The graphs of media-handling components are chained in a pipeline for the sending and receiving party. The sending party instantiates the Gstreamer software by defining the source (file, input device, etc.), applies encoding on the data stream and optimally packages the stream into data chunks transported over e.g. Real-Time-Transport-Protocol (RTP). The receiving side processes the pipeline in revers order to display finally or process the content further on. The major decision for GStreamer is the support of the x264enc pipeline element, which supports dynamic bandwidth adaptation through changes of the bit rate.

GStreamer has been selected after an extensive comparison and evaluation of existing solutions. Since the focus has been on adaptive streaming solutions, only a few have been identified and even less are available Open Source.

The choice of GStreamer is motivated due to the fact, that GStreamer is flexible, platform independent and supports various codecs and adaptive streaming. These criteria are expected as highly crucial in the selection of multimedia streaming approaches shown in C.1 .

Summary

	Akamai	MS SVS	Apple	Adobe http	Adobe RTP	MMGW	Ice (Gstreamer)	MPEG DASH
Type	Solution	Solution	Standard + tools	Solution	Solution	Research/ prototype	Framework	Standard
License	Propr.	Propr.	Propr.	Propr.	Propr.	Research	GNU	
Codecs	H.264/MPEG4	MP4	MPEG-2 TS	MP4, flv	MP4, flv	?	Many	MPEG
Controller	Client	Client	Client	Client	Client	-	Client	Client
Encoding on the fly	No	No	No	No	No	Yes	Yes	No
Supported by	Akamai + its clients	MS	Apple	Adobe	Adobe	-	Open source world	3GPP + MS + others
OS supported	Supports next 3	Windows, Linux, ~ iOS	iOS	All with flash	All with flash	Any	Linux, Windows	Any
Protocols	http	http	http	http	Rtmp	?	http	http
Fragment size	?	2s+	10s+	?	N/A	-	Any	variable
Programming	-	.NET clients	Objective-C	ActionScript	ActionScript	-	C	Any
Unsuitability reason	Closed solution	Closed solution	limited to apple	Closed solution	Closed solution	Requires complex infrastructure	No out-of-the-box solution	No out-of-the-box solution

Figure C.1: Comparison of Multimedia Streaming Approaches

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