V2X Communication in Heterogeneous Networks

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At this point, I want to express my gratitude to all people who have contributed to this work. A fundamental characteristic of the radio signal reception is that the signal experiences contributions from multiple paths. A fundamental design principle of communicating vehicular applications is to gather information from many sources and senders in the surrounding. Both pattern are really close to what I experienced with me and my thesis. Accordingly, I am pleased to say that I could all the time rely on input in many different - direct and indirect - ways.

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Abstract

Future intelligent transport systems will be based on digital networking of vehicles and infrastructure for mutual information exchange. This will enable many new applications to increase traffic safety and efficiency as well as new comfort services. How digital networking should look in concrete terms is now being researched from different directions. The basis will be wireless communication systems. So much is clear. However, there are mainly the two possibilities of ad hoc networks with purely decentralized communication as well as cellular mobile networks with existing infrastructure. The present paper examines heterogeneous solutions in which both communication systems exist. Accordingly, it is possible for the two communication systems to complement each other sensibly in certain scenarios in order to fill corresponding technological gaps.

In principle, the various applications also have different characteristics and requirements for communication technology. For example, in traffic safety and efficiency applications there is an information exchange between many endpoints, while personal comfort applications are generally limited to two points, the client and the server. Tolerable communication latencies are more strict for security than for efficiency applications and so on. For these reasons, this work begins with a classification of planned "Day One" applications and current application trends. In addition, a technical assessment metric is introduced, in particular to enable the comparison of the mobility-related applications.

The main part of this thesis deals with the simulative comparison of heterogeneous ad hoc and cellular communication approaches. The V2X Simulation Runtime Infrastructure (VSimRTI) is improved and expanded in different ways. Since the modeling of the radio signal propagation has a great influence on the communication characteristics for ad hoc networks, the simulation environment is extended. On the one hand, an approach to the deterministic simulation of buildings and their shading effects is developed. On the other hand, advanced models are presented which statistically model the relevant fading and shadowing effects. An approach is also being developed for the modeling of cellular communication, namely a completely new simulator VSimRTI_Cell. A complete mobile network can be very complex. Therefore, a simulation setup that models each individual node of the system individually would quickly reach its limits in larger vehicle scenarios. For this reason, VSimRTI_Cell offers an efficient abstraction for the modeling of an entire mobile network, i.e. both the radio access network and the core network.

The last part of this work combines the previous work packages in a simulation study. This study analyzes reference applications for the most important classes of traffic safety and efficiency applications using the proposed assessment metric CCP. The applications are not only investigated in isolated scenarios, but are simulated together in a heterogeneous scenario to investigate the interactions of ad hoc and cellular communication technologies.

Zusammenfassung

Zukünftige intelligente Transportsysteme werden auf der digitalen Vernetzung von Fahrzeugen und Infrastruktur zum gegenseitigen Informationsaustausch basieren. Dadurch werden viele neue Anwendungen zur Steigerung von Verkehrssicherheit und Effizienz, aber auch neuen Komfortdienste ermöglicht. Wie die digitale Vernetzung konkret aussehen soll, wird heutzutage aus verschiedenen Richtungen erforscht. Die Grundlage werden drahtlose Kommunikationssysteme bilden. Soviel ist klar. Jedoch gibt es hier vor allem die beiden Möglichkeiten von Ad-hoc-Netzwerken mit rein dezentraler Kommunikation sowie zellulare Mobilfunknetze mit existierender Infrastruktur. Die vorliegende Arbeit untersucht heterogene Lösungen, bei denen beide Kommunikationssysteme existieren. Dementsprechend ist es möglich, dass sich die beiden Kommunikationssysteme in bestimmten Szenarien sinnvoll ergänzen, um entsprechende technologische Lücken zu füllen.

Grundsätzlich weisen die verschiedenen Anwendungen auch unterschiedliche Eigenschaften und Anforderungen an die Kommunikationstechnik auf. Beispielsweise gibt es bei Verkehrssicherheits- und Effizienzanwendungen ein Informationsaustausch zwischen vielen Endpunkten, während persönliche Komfortanwendungen in der Regel auf zwei Punkte, den Client und den Server, beschränkt sind. Tolerierbare Kommunikationslatenzen sind für die Sicherheit strenger als für Effizienzanwendungen. Aus diesen Gründen beginnt diese Arbeit mit einer Klassifizierung geplanten “Tag Eins”–Anwendungen und aktuellen Applikationstrends. Darüber hinaus wird eine technische Bewertungsmetrik eingeführt, um insbesondere den Vergleich der mobilitätsbezogenen Anwendungen zu ermöglichen.

Der Hauptteil dieser Arbeit befasst sich damit den simulativen Vergleich von heterogenen Ad-hoc- und zellularen Kommunikationsansätzen zu ermöglichen. Dafür wird die V2X Simulation Runtime Infrastructure (VSimRTI) auf unterschiedliche Weise verbessert und erweitert. Weil für Ad-hoc-Netze besonders die Modellierung der Funksignalausbreitung einen großen Einfluss auf die Kommunikationseigenschaften hat, wird die Simulationsumgebung dahingehend erweitert. Zum einen wird ein Ansatz zur deterministischen Simulation von Gebäuden und ihren Abschattungseffekten entwickelt. Zum anderen werden erweiterte Modelle

vorgestellt, welche die relevanten Fading- und Shadowing-Effekte statistisch modellieren. Auch für die Modellierung von zellularer Kommunikation wird ein Ansatz entwickelt, und zwar ein neuer Simulator VSimRTI_Cell. Ein komplettes Mobilfunknetz kann sehr komplex sein. Deshalb würde ein Simulationsaufbau, der jeden einzelnen Knoten des Systems einzeln modelliert, in größeren Fahrzeugszenarien schnell seine Grenzen erreichen. Deswegen bietet der VSimRTI_Cell eine effiziente Abstraktion zur Modellierung eines gesamten Mobilfunknetzes, also sowohl Zugangsnetz als auch Kernnetz.

Der letzte Teil dieser Arbeit vereint die vorangegangenen Arbeitspakete in einer Simulationsstudie. Diese Studie analysiert Referenzanwendungen für die wichtigsten Klassen von Verkehrssicherheits- und Effizienz-Anwendungen unter Verwendung der vorgeschlagenen Bewertungsmetrik CCP. Die Anwendungen werden nicht nur in isolierten Szenarien untersucht, sondern zusammen in einem heterogenen Szenario simuliert, um die Wechselwirkungen von Ad-hoc- und zellularen Kommunikationstechnologien zu erforschen.

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Chapter 1

Introduction

This chapter gives an introduction to this document. Initially, the motivation for the work is presented. Afterwards, the contributions and the scope of this thesis are stated. The final section of this chapter outlines the general structure of the document.

1.1 Motivation

Over the last decades, electronics and information technologies emerged to be the key factor for innovation in the automotive world. The Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, which is overall referred to as Vehicle-to-X (V2X) communication or Inter-Vehicle Communication (IVC), is a research area of particular interest. A great number of envisioned use cases raise high expectations for the introduction of this technology in future generations of vehicles. The terms Intelligent Transportation Systems (ITS), respectively Cooperative ITS (C-ITS), are also often used in relation with communicating vehicles. These terms especially refer to the use cases that will help to increase the safety and efficiency of road transport. From a holistic view, many other digital functions, which are e.g. connected with Internet based services, can also be applied in the vehicles.

Essentially, the research in V2X communication faces two areas of challenges, stemming from

1. the nature of the use cases themselves and
2. the physical characteristics of the vehicular environment.

First, the responsible stakeholders for the introduction of the V2X communication technology to the daily life are mainly interested in the potential use cases.

Today, the integration of mobile devices like smartphones decouples the different development cycles in consumer and automotive electronics. Hence, many communication use cases, which keep the human in the loop like e-mailing, browsing or media streaming, are already available in vehicles. Moreover, location-based services are of special interest due to a major intention of vehicles, which is moving from one location to another. All these use cases base on the conventional communication pattern with a direct connection between two nodes. In contrast, the use cases that rely on communication of machine to machine (M2M) cause completely new paradigms. Such use cases would not address only a single communication partner, but multiple ones in the local neighborhood. From the related field of robotics, it is known that control loops exhibit tight real-time constraints. In this manner, the information of the parameters to be processed in such loops is rather small (measured in bits), but needs to arrive in time. The same applies for M2M-communication use cases. Due to the dynamic changes of the vehicular driving situations, the information becomes outdated and needs to be periodically refreshed, which means periodically retransmitted. In fact, M2M-communication use cases are promised to have the highest potential to shape the future situation in the automotive transport. Particularly, these use cases can improve traffic safety and efficiency. Vehicles that communicate with their neighbors are able to anticipate critical traffic situations and inform their drivers earlier. Moreover, vehicles can feed the received information to their assistant systems to facilitate safe driving maneuvers based on cooperation.

Nevertheless, the introduction of M2M-communication based use cases to the vehicles is a difficult task. It is different from others as it needs a minimum of networking partners to communicate. Especially, early customers will need to wait upon a certain market penetration until they can perceive the functionality, they have paid for. Instead, the traditional way since introduction of the earliest electronic components to vehicles realizes new safety features locally in the vehicle, mainly with more sophisticated sensors. For example, electronic stability control uses gyroscopes; adaptive cruise control relies on radar to extend the view of the system. Sensor technology for the emerging field of autonomous driving relies on an integrated setup of radars, 3D lidars and (stereo)-cameras. Besides the directly arising benefits, this way keeps another considerable advantage for the automotive engineers that influenced their mindset to a great extent. When they assure that the own sensors work correctly, they can trust the gathered information and do not need to care about information security. In contrast, external information always includes the potential to originate from defect components of the other participants or even being intentionally manipulated. For the drivers, communicating vehicles might imply less privacy as somebody can track their vehicles and routes.

Second, the wireless communication engineers meet other challenging problems when they approach the topic from their perspective. The vehicular environment possesses very special communication characteristics. It is very heterogeneous, ranging from urban scenarios, with dense building development to shadow the signal propagation, to rural areas without these so-called scatterers. The possibly high relative speeds of the vehicles induce physical distortions of the information signal. Moreover, the mostly different routes of the vehicles lead to continuously changing neighbors. In the early stage of introduction as well as in low traffic periods, there will be few communication partners and sparse connections. In contrast, there will be high densities on major roads in rush hour periods. In networking terms, these characteristics lead to continuously changing connections and communication partner densities. In other words, scalability of the communication system is a very important issue.

Anyway, despite certain concerns, cooperation using V2X communication technology is definitely a further step for new innovations in safety and efficiency that cannot be achieved with standalone technologies. Security and privacy need to be considered for sure. Moreover, it helps to prove that V2X communication really outperforms relying only upon local sensors to gain acceptance from the stakeholders. Therefore, Figure 1.1 sketches the individual landmarks in the innovation space for improvement of traffic safety and efficiency. Please note, that safety and efficiency depend on and mutually facilitate each other. More efficiency reduces the stress for the drivers, and accordingly the probability of disorder. The avoidance of accidents due to more safety leads to higher efficiency. The innovation space spans from the current situation (Now) to the limitations of the vehicles' brakes, engines or tires and so on (Physical Optimum). Certainly, this limit can be shifted in the direction to increase safety and efficiency with better physical components. However, this is out of scope what the communication technology can contribute. Assuming all information is available and meets the timing constraints of the control-loops, there might be still inevitable accidents. This landmark (Ideal Knowledge) can probably be shifted in the direction of the physical optimum with better processing in the actuators, but is the limit for the information system. Assuming the vehicular environment with a certain communication channel, where information can be delayed or even never reach the destination at all, sets the Information Theoretical Limit. Finally, the success depends on applications and protocols of the V2X communication technology.

It is a difficult task to localize this particular landmark in the innovation space as it implies a multidisciplinary discussion with security engineers, traffic experts, and psychologists and so on. When insufficiently designed, V2X communication technology can be still worse than the realization with perfect local sensors, especially when wrong information is disseminated.

A commendable approach tries to tackle the problem of proving the impact of V2X communication technology in the following way. It starts with the requirements of use cases and derives, from this point, the properties for the

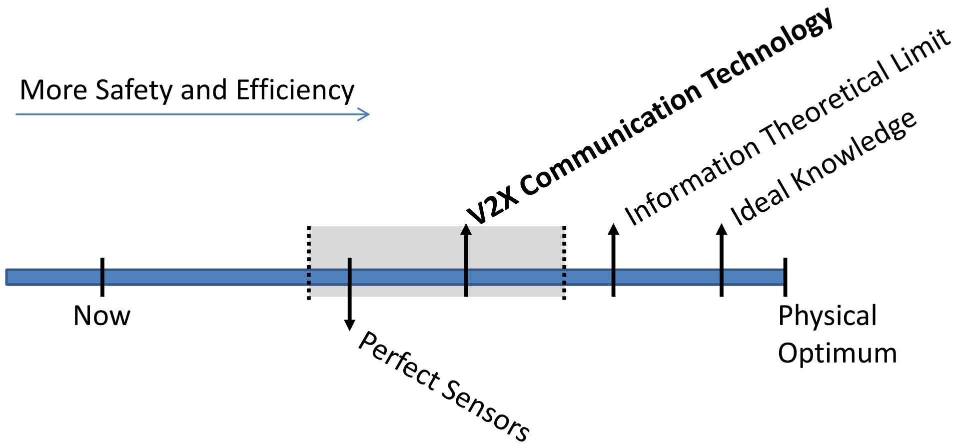


Figure 1.1: Innovation space for the improvement of Traffic Safety and Efficiency

design of the communication system. This approach is sometimes referred to as top-down to distinguish it from starting with the communication channel, protocols and algorithms - in this context known as bottom-up. The bottom-up approach is the traditional way communication engineers have designed today's information network systems. However, the sole top-down approach still exhibits certain problems. Initially, the exact functionalities and requirements of the use cases need to exist. Today, there are already many use cases envisioned with many different requirements. Moreover, there are often many ways and applications to implement a use case. In this manner, the use cases need to be classified to avoid going the top-down approach many times. As the case, design indications may be too imprecise when fewer details are considered for the categories. Moreover, derived design indications can be contradicting for different applications or even be impossible to realize.

The example of a V2X supported overtaking assist, depicted in Figure 1.2, should serve as an illustration. In this case, a driver in the Ego vehicle should be assisted for safe overtaking of a larger Truck, which obstructs the view towards possibly opposing traffic (vehicle Opp). Even advanced sensors like cameras or lidars would not be able to determine oncoming objects as early as communicating vehicles can. Two different solutions with different communication properties can be imagined immediately. Certainly, there are many more.

1. The Opp vehicle is equipped with a satellite navigation system (e.g. GPS) and V2X communication technology and sends information about its position vector, including the position, heading and speed. The Ego vehicle, which also uses GPS and V2X, receives this information. With the own and the received trajectories, it can calculate whether the overtaking maneuver is safe or not. Afterwards, it can inform the driver or initiate the maneuver in case

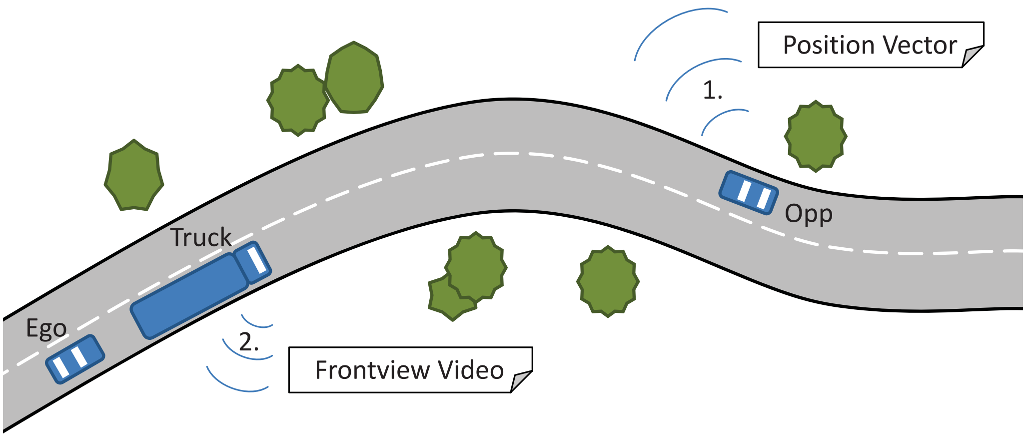


Figure 1.2: Scenario for an overtaking assistant with two alternative solutions

of autonomous driving. In this solution, the information to be exchanged is relatively small when it comes to bits. However, the information needs to arrive at Ego in time, which means at least before Ego on its own can see Opp. Otherwise, the driver would not perceive an additional benefit from the V2X communication technology. However, the critical issue in this implementation is that Ego cannot be sure that there is no one in the oncoming traffic, when it does not receive the information. In such a use case, a false negative error - meaning there is an oncoming vehicle but no indication - cannot be accepted. Hence, the solution is only safe when de facto all vehicles are equipped with the V2X communication technology AND the information from the relevant vehicles definitely arrives at Ego.

2. The Truck uses a front view camera and streams the captured video over V2X communication. Upon reception, Ego can either directly display the video for the driver or computationally analyze the video for oncoming vehicles. In this way, Egos view extents compared to local camera sensors. This solution also requires in-time transmission and short delays for the video to be accepted. Moreover, the video should exhibit a certain resolution to distinguish a possibly oncoming vehicle from other objects in the setting. The size of the video would definitely exceed the size of the position vector from solution 1). For many participants, such a resource intensive solution would possibly lead to a bottleneck of the communication channel. Nonetheless, the solution already works from the beginning for every equipped truck. It can be introduced gradually, even if there are still unequipped trucks remaining.

The example shows several aspects for the sphere, where the V2X communication system is designed. First, several application solutions can address the same use case. The different solutions exhibit very different communication properties. A possible top-down investigation would suppose different design directions for the underlying system. Second, one of the most important aspects is that certain solutions enable a nearly immediate benefit for early adopters, while others need a minimum penetration rate of communicating partners to work. For solution 1) from the example, the minimum penetration rate is even 100%.

The evolution of V2X communication technology will take a similar way as already seen at the other communication systems, e.g. recently the mobile Internet access in connection with smart devices. Back then, when the third generation broadband wireless networks were developed, communication engineers thought deeply about must-have use cases that justify the capable specifications. Now, when the communication systems have a mature stage and open interfaces for experts from other domains, the variety of use cases has grown tremendously. When the communication facilities are available, applications will follow and probably turn out different regarding the requirements, than estimated today. Of course, the communication system needs to be flexible enough to be tuned for the use case requirements. This means that the top-down approach to derive the requirements for the system and the bottom-up approach to develop the capabilities need to go hand in hand.

From technical perspective, two alternatives are currently envisioned to realize the V2X communication system. Each alternative exhibits its individual advantages but also disadvantages compared to the other one. First, there is the concept of ad hoc networks. This alternative has a long relevance in the academic community. The term VANETS (vehicular ad hoc networks) was and still is a prominent synonym for V2X communication. VANETS are based on wireless LANs with communication in the ad hoc mode. This approach already offers many advantages for the specific needs of the M2M-communication use cases. The direct communication allows short latencies and short messages. Moreover, the direct exploitation of the broadcast-characteristics of the wireless channel is possible. However, the scalability is a big challenge in this approach, due to the limited communication range. For spanning longer distances, messages need to be relayed. On the one hand, in sparse network situations, no communication would be possible. This would be the case in the early stage of the market penetration, as well as in areas or at times with low traffic. On the other hand, too many participants are a problem as well, when the communication medium gets congested. After intensive efforts, researchers have found solutions to many problems and have tailored protocols to meet the specific characteristics. Field trials were set up to show the maturity of the system. Still, the landmark where V2X communication technology is localized in the innovation space (Figure 1.1) is not convincingly positioned, especially for the Day One situation with view participants. The second alternative uses infrastructure based cellular networks not only for Internet services, but also for traffic safety and efficiency matters. Cellular networks exhibit the major advantage of a nearly unlimited communication range, due to the architecture with only a short wireless part between the mobile device and the base station and the wired part through the backbone. However, the current generations are not primarily designed for the specific needs of vehicular use cases with the M2M-communication pattern. The systems are optimized for high data rates without real-time requirements. Moreover, a partial technical problem arises due to the different cellular networks by different operators.

Even though, the situation appears to be dominated by a competition of the factions, which favor either ad hoc or cellular based technologies. This thesis will also investigate the cases when both approaches complement one another. The introduction of V2X communication will not be a uniform process. It will include one part of users to decide first equip their vehicles with a cellular solution and one part with an ad hoc solution. In this way, this thesis proposes the statement that heterogeneous vehicular networks are important to leverage use cases for communicating vehicles.

1.2 Contribution

This thesis aims to answer the question of the benefit to focus on heterogeneous concepts for the development of V2X communication applications in the following way.

First, it will investigate the currently envisioned use cases and application trends for connected vehicles to derive the requirements of the V2X applications for the underlying communication systems regarding important parameters as transmission latencies, packet errors, amount of data and so on. Certainly, due to the diversity of the applications, the requirements would also turn out differently. For instance, use cases that require a higher communication horizon typically exhibit less critical performance for the transmission latencies. For this reason, this thesis will establish a classification of the applications for the later evaluation. This part of the thesis comes close to the mentioned top-down approach.

The second major objective of the thesis concerns the identification of the technical capabilities of the communication systems to approach the topic from the bottom-up perspective. Moreover, it aims to adapt and extend a simulation environment to model the relevant aspects of the different access technologies. The basis is the V2X Simulation Runtime Infrastructure (VSimRTI), which was developed in a previous work at the department. To allow comprehensive investigations of vehicular communication scenarios, VSimRTI couples state-of-the-art simulators from different domains such as traffic, wireless communication and vehicular applications. However, with the specific focus on communication characteristics and, more precisely, on heterogeneous networks, the simulation environment needs to be extended. The ad hoc communication simulator will receive advanced models to regard for important aspects of the radio propagation, such as fading and shadowing on buildings. For cellular communication, a completely new simulator, which incorporates the wireless as well as the wired part of a cellular network, will be developed. The new features will be presented with individual simulations studies. Actually, this part denotes the core work of the thesis.

Finally, the thesis compares the advantages and disadvantages of the ad hoc and cellular communication approach with a concluding simulation study. The results will be evaluated with communication metrics that regard especially for the presented envisioned applications. Moreover, the applications and communication technologies will not be investigated in isolated scenarios, but the simulated together in one scenario to explore the interdependencies. A hybrid approach that uses both communication technologies, will benefit from the low latencies of the ad hoc path and the robust and high-range communication of the cellular path.

1.3 Thesis Structure

The content of the individual chapters in this thesis is given as follows.

- This Chapter 1 already introduced the general sphere of the present work and stated the objectives, which are to be pursued.
- Chapter 2 provides an overview of the V2X communication system. It starts with the envisioned applications which should be introduced from day one to select a subset of applications, which are evaluated later in Chapter 5. Moreover, the standardized systems for V2X communication are introduced.
- Chapter 3 presents a comprehensive overview on the underlying wireless communication technologies. From bottom-up, it starts with the radio channel and afterwards discusses the characteristics of ad hoc as well as cellular systems.
- Chapter 4 describes the modeling and implementation efforts to simulate the previously introduced communication characteristics. This work enables the simulation analysis in the following Chapter 5.
- Chapter 5 performs a simulation study to evaluate the previously selected applications regarding the benefits of a hybrid ad hoc and cellular approach in an integrated scenario.
- Finally, this treatment is concluded in Chapter 6 with respect to the initially stated aims. The outlook identifies open research questions for future work in the area.

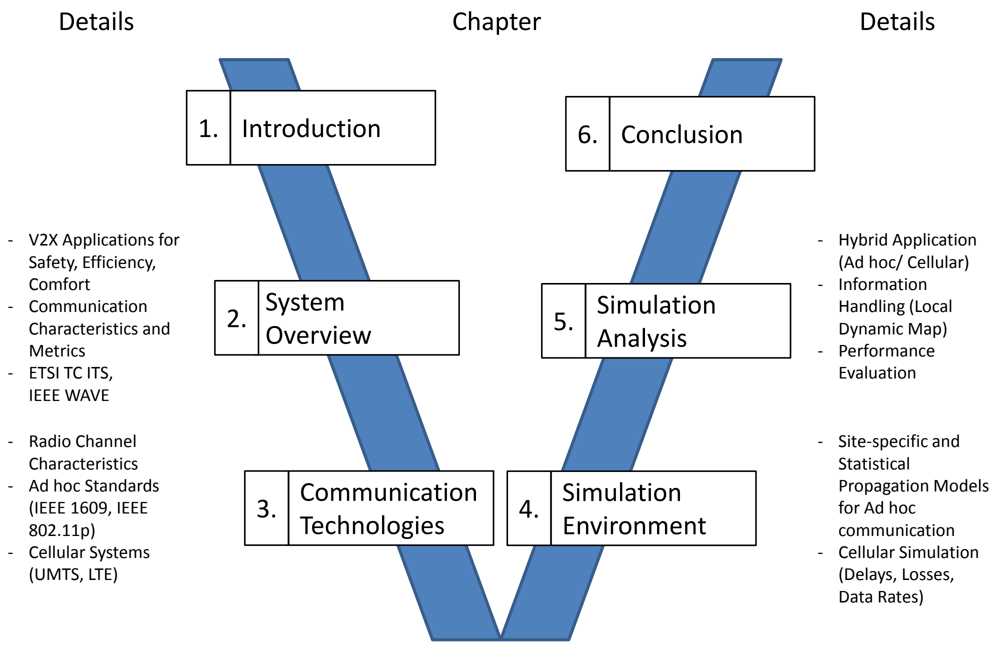


Figure 1.3: Structure of this thesis as V-model

Figure 1.3 illustrates the structure of this thesis and the correlation between the individual chapters. The V-model is a very popular process model in the automotive system and software development. Although, this model originally describes a slightly different context of tests to verify specifications, it also suits here for the relationship of the thesis chapters. Consequently, the development in Chapter 4 applies to the introduced principles of communication technologies in Chapter 3. The evaluation in Chapter 5 particularly refers to the applications and the system architecture from Chapter 2. Finally, Chapter 6 resumes the objectives that are stated previously in this Chapter 1.

Chapter 2

System Overview

This chapter introduces the basic principles and architectures for vehicular communication. It starts from the perspective of the applications and describes their specific requirements towards the underlying communication system. Afterwards, a suitable metric is derived that accounts especially for the requirements of safety applications. Finally, this chapter presents the most suitable systems that are currently being developed by the major standardization bodies as well as the research community.

2.1 Envisioned Applications

As mentioned in the introduction, the usage of communication in the automotive environment enables a huge number of different use cases and applications. Today, the ITS working group from the ETSI (European Telecommunications Standards Institute) maintains the most recognized catalog of application specifications for the introduction of V2X communication technology [ETS09, ETS10b]. The specifications are also known as the basic set of applications. They received contributions from the Car-to-Car Communication Consortium (C2C CC) [CAR07] and especially from the European research project PRE-DRIVE C2X [PRE08]. Altogether, the ETSI documents list more than fifty (namely 53) use cases for different aims. Some of them keep the human in the loop. Most of them base on M2M communication. Hence, the classification of applications is necessary to focus the work on the important issues and reduce the set of regarded applications in the later evaluation.

2.1.1 Existing Classifications

The most common application classification in the literature divides the use cases into three major categories with respect to their intended purpose [CAR07].

1. The first class of applications aims to warn and assist the driver in certain maneuver situations and increase the traffic **safety** in this way.
2. The second class informs the driver in a slightly longer perspective and can improve the traffic **efficiency**.
3. In the third class, there are **comfort** applications that are not directly related to the vehicles' mobility, but are part of today's digital life style. Another aspect of this group is that these applications can be realized on individual basis and not rely on cooperative M2M information exchange. These applications are also referred to as **infotainment** applications.

A second classification is even located one step prior to that, and rather takes the perspective of a car manufacturer [KSSB12]. There, the class of **vehicle-related** applications establishes the connection to certain components of the vehicle over different wireless and even wired communication technologies. Examples include Ethernet-based connections for remote management of control units for failure diagnosis or software updates. Moreover, the connection of mobile phones and devices to the audio and navigation onboard unit via Bluetooth or Near Field Communication (NFC) or even USB are regarded. The second class of **passenger-related** applications conforms most to the comfort category from the first classification and includes, amongst others, information provisioning services as E-mail, personalized entertainment as media streaming or convenience services for wireless payment. Both categories have in common that their applications have no direct impact on the vehicular traffic situation. In contrast, the third class of **driving-related** applications exchanges and provides the information for the driver or the assistance systems to influence the vehicle's driving state. This class covers all use cases of the safety and efficiency classes from the first classification.

A third view according to the road safety application model from the ETSI can serve particularly to illustrate the characteristics of the driving-related safety and efficiency applications [ETS13b]. Figure 2.1 depicts the position of the different information zones in relation to the time to a possible incident, using the metric of the TTC (time to collision) according to the equation of motion (Equation (2.1)) with $\vec{r}$ as the location and $\dot{\vec{r}}$ as the derivation of the location (namely the speed) of two related nodes i and $i-1$.

$$TTC_i = \frac{\vec{r}_{i-1}(t) - \vec{r}_i(t)}{\dot{\vec{r}}_i(t) - \dot{\vec{r}}_{i-1}(t)} \rightarrow d = |\vec{r}_{i-1}(t) - \vec{r}_i(t)| = \left(\dot{\vec{r}}_i(t) - \dot{\vec{r}}_{i-1}(t)\right) TTC_i \quad (2.1)$$

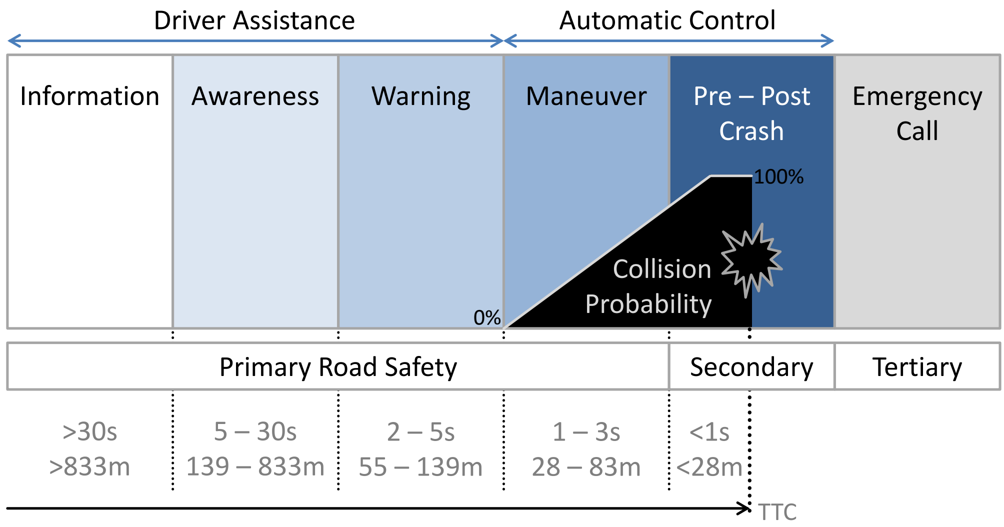


Figure 2.1: Zones of the road safety application model (based on [ETS13b])

All values for the TTC should be accepted with caution as exact values are indeed very difficult to define. Even according to the ETSI, the given values are not finalized yet and mainly intended as examples. Figure 2.1 includes additional values for the distance towards the incident. These values are simply calculated for the TTC of the individual zones, in a situation where two vehicles approach each other with a constant speed of 50 km/h (13.89 m/s). Different situations (e.g. different movement constellations or vehicle speeds) would obviously lead to other values here.

The leftmost zone of the model contains all applications for driver **Information**. Such applications have the most relaxed timing requirements in this model and no critical safety relevance, yet the highest distance to the situation. In fact, these applications conform most likely to the traffic efficiency applications from the first classification [CAR07]. There is a smooth transition from safety to efficiency applications as it is also between the individual safety applications with soft and hard timing constraints. The next zones for **Awareness** to inform the driver about road hazards, and for **Warning** to signal possible collision risks, still contain applications for driver assistance. The **Maneuver** zone is characterized by an increasing collision probability and a TTC that is below the reaction time of most drivers. Hence, this zone is the last one that contains primary road safety applications to avoid collisions. However, the collision avoidance and stabilization would only be possible with the active engagement of the vehicles' automatic control systems. Additionally, the model also contains secondary safety applications in the zone where the collision probability reached 100 % and a **Crash** is inevitable. Finally, tertiary **E-call** applications aim for safety relevant actions after the incident took place [ETS13b].

2.1.2 Application Selection

The already existing classifications are convenient to provide a first overview of the different applications. In a broader sense, all three classifications agree to the partition of applications to the categories of safety, efficiency and comfort. When employed for the 53 candidates from the ETSI basic set of applications, there are 23 safety, 11 efficiency and 19 comfort applications. When concentrating only on the ITS related safety and efficiency applications, all safety and 7 from 11 efficiency applications rely on a very characteristic communication pattern with regular information exchange to inform multiple neighbors in the vicinity. Exceptions from this pattern apply to the two connected V2V use cases of cooperative adaptive cruise control and platooning, as well as to the V2I use cases of enhanced route guidance and navigation, and electronic toll collect. These use cases would require a session-based information exchange [PRE08]. The remaining 30 applications can be further distinguished with the following additional classifiers.

The Situation Duration indicates whether the information exchange needs to occur **permanently** as long as the vehicles participate in the traffic situation, or is **temporary** limited to a certain time span. According to this definition, the situation would also regard to a vehicles' state and position. All efficiency applications and particular safety applications, which enable cooperative awareness, usually involve a permanent information exchange. In contrast, certain safety applications rely on time limited communicate to give notifications about specific events. The ETSI distinguishes applications with this classifier according to the message content of Cooperative Awareness Messages (CAM) [ETS14a] for permanent and Decentralized Environmental Notification Messages (DENM) [ETS14b] for temporary information dissemination.

The Situation Location ranges from **stationary** to **moving**. The definition of the stationarity of the situation depends on the vehicle speed. For instance, the end of a traffic jam actually also moves, but compared to the vehicles with a significantly lower speed. The information about locally stationary situations needs to be received only once at a specific distance for a driving vehicle to be acceptable for a successful use case. Moving situations typically regard for awareness updates of individual vehicles and demand a regular information refresh, whereas the update period is connected with the moving speed of the according vehicle.

The Reporters can be either a **single** one or **multiple** nodes. When information from a single reporter is important for the successful use case, the reception quality and the communication latency for the single messages are crucial issues. When multiple reporters inform about the same situation from their perception, the individual reporter is of minor importance and single messages can arrive delayed at the potential receivers or even get lost, as there would still be the feasibility to receive similar information from another reporter.

After employing the classifiers to the remaining 30 applications, the following conclusions can be stated.

- In all 7 efficiency applications, single stationary infrastructure nodes permanently report about the current state of the traffic situation. This regards for long-term or even unchanging situations as regulatory speed limits, but also for short-term situations as the signal phases of traffic lights in the use case of the green light optimal speed advisory. The critical requirement of these applications regards for a high range of information dissemination.

- In 13 safety applications, moving vehicles permanently report their current state information matched to their location to create cooperative awareness. For instance, the emergency vehicle warning use case is also part of this category, whereas the emergency vehicle is a special vehicle that could also take part in the traffic without informing other about its priority state. Compared to efficiency applications, these applications exhibit time-critical communication requirements. Still, the speed and direction information in the exchanged position vectors allow for the bridging of certain time spans without reception and information refresh.

- In 5 safety applications, vehicles report state information for a limited time span when a certain event is detected. An example is the detection of a hard braking event for an emergency electronic brake light warning. Regarding the communication requirements, these applications conform to a large extent to the previously mentioned safety applications with one significant difference of the instant need for communication without prior notice and thus without the feasibility of prior tracking by the receivers. As similarity, the 5 and 13 safety applications are not suited for storing and re-transmitting the information about the moving vehicles as this gets constantly outdated.

- In 4 safety applications, vehicles as well as stationary nodes report about stationary situations for a limited time span. The use cases of the stationary vehicle - and the roadworks warning are initially specified with only a single reporting node. Due to the stationarity of the location, these use cases also qualify well to be extended that multiple reporters forward the information as it is the case with the other two use cases of hazardous location - and traffic condition warning, in this category. At a price of increasing the data traffic, this approach would extend the robustness of a use case as the dissemination of redundant information allows for individual losses.

- Finally, the last application of decentralized Floating Car Data (FCD) aims to identify certain traffic situations from the permanently received information of multiple moving reporters. The use case can be the basis for other safety use cases, e.g. when a traffic jam is identified. In this way, it also enables efficiency use cases. Consequently, the FCD application should be of interest for the final simulation study in this thesis.

In summary, the application selection presented that the most important communication paradigm for ITS related safety and efficiency application bases on regular information dissemination from individual traffic participants to their neighbors. When use cases regard for a stationary situation, the reception of a single one out of multiple messages from the reporter is sufficient. Moreover, these use cases can be extended that multiple reporters increase the redundancy. When such stationary situations should be combined with efficiency, the possibly high range of information dissemination would be the critical parameter for the underlying communication system. The applications with a single moving reporter require a short delay and regular refresh of information as contrasting parameter. Hence, the specific architectures to enable V2X communication use cases need to account for these challenges. Prior to the introduction of the communication systems, the appropriate communication metrics should be presented to measure the two requirements.

2.2 Communication Metrics

2.2.1 Classical Communication Metrics

The classical approach to evaluate the quality of information exchange bases on the Packet Delivery Ratio (PDR). This metric defines the number of successfully received messages out of all sent messages [Rap02]. Depending on the application, either all or a certain percentage of sent messages can be required to be received that the applications can work sufficiently. In fact, for successful operation of most V2X communication use cases, not every sent message needs to be received, as messages can contain similar information.

The PDR as a function of the distance already contains valuable information, which should be explained at the following example. Assume the PDR trend for a typical wireless ad hoc communication link according to the IEEE 802.11p standard, as presented in Figure 2.2 (black graph). The displayed PDR stems from a scenario that already includes the typical impairments found in realistic vehicular communication environments, as a fading radio channel and message collisions due to uncoordinated medium access by multiple nodes. The PDR

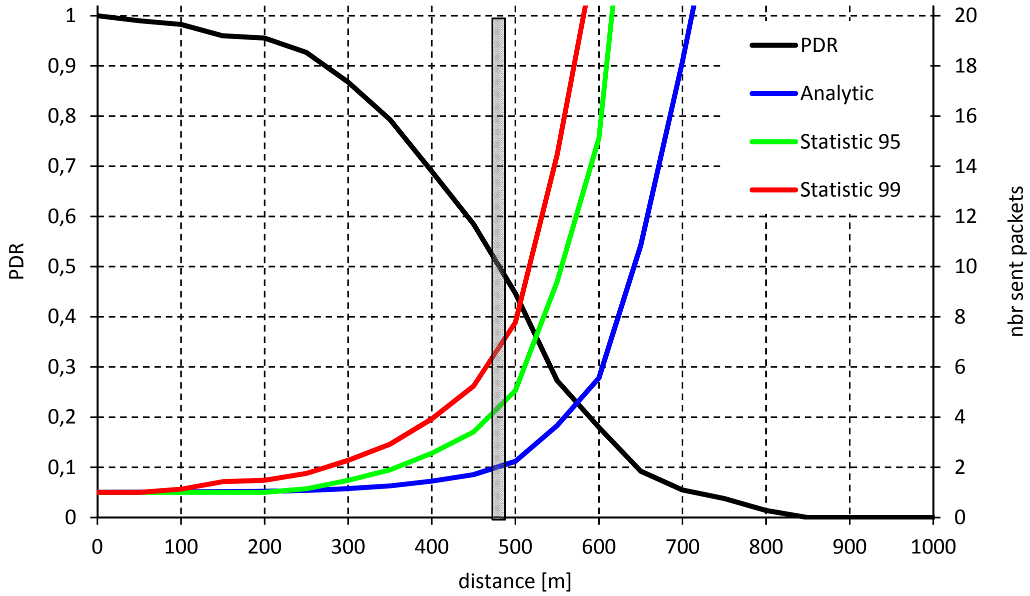


Figure 2.2: PDR in relation to the implied numbers of sent messages for a successful reception according to the analytic and statistic approach

declines to 0 at the distance of 800 m. This distance denotes the maximum communication range. According to the ETSI road safety model (Figure 2.1), information safety applications could be facilitated in this way [ETS13b]. The other graphs in Figure 2.2 show the number of messages that need to be sent for the reception of exactly one message. These graphs are derived from the PDR according to different approaches.

- The analytic approach uses merely the relation $\frac{1}{PDR}$ and can be seen as the optimistic estimation. The respective graph in Figure 2.2 is the blue one.
- The statistical approach uses the success probability for a series of retries and requires the success probability to be higher than a given confidence interval. This approach denotes the realistic case. Figure 2.2 displays the case of a probability using typical confidence intervals of 95 % (green) and 99 % (red).

The diagram can be interpreted in the following way: When e.g. the $PDR = 1$, every message is received. This means for the optimistic as well as the realistic case, that only one message needs to be sent in order that one message can be received. When the $PDR = 0.5$ (shaded rectangle in Figure 2.2), the results are different for either case. In the optimistic case, 1 message is received when at least 2 messages are sent. In the realistic case, 1 message is received with a probability higher than 95 % (actually 96.9 %) when 5 messages are sent. The number of sent messages for the reception success increases to 7 in the more stringent case of 99 % accordingly. When the draconian success probability of exactly 100 % of message reception would be required, the number of sent messages would tend to infinity in the case where the PDR is unequal to 1.

When a certain sending rate f_s, equivalent to periodical CAMs, is assumed, the number of sent messages implies a timing constraint. The actual communication characteristics are then located in the corridor between the optimistic and the realistic case. Nonetheless, this corridor between optimistic and realistic case can be very large, which implies a limited informative value of the PDR. A previous study employed the PDR to measure the influence of communication properties on a navigation application [PSR11]. For different applied propagation models, the PDR also turned out different. In contrast, the application was not sensitive to these differences, as multiple messages with similar content could be received. Accordingly, in this case the PDR is not powerful enough to find the certain situation where the application performance changes.

Another classical communication metric that can cover timing properties is the transmission latency. It defines the delay from the message sending attempt to the reception. However, this metric is only useful to a limited extent for communication modes where packet reception and losses can be acknowledged. This would be the case in managed cellular systems and ad hoc communication in the unicast mode. Yet, for V2X applications, the more interesting case employs the broadcast mode to concurrently inform all neighbors in the vicinity with one message as a CAM. Especially, this mode involves the probability of unnoticed packet losses. Hence, the transmission latency and the PDR need to be combined for a more significant measure, which is the Consecutive CAM Period (CCP) [PSR14b].

2.2.2 Application Layer Metrics

Basically, the Consecutive CAM Period (CCP) is the time between two successfully received CAMs, which are the messages that are permanently reported to create cooperative awareness. The CCP can be represented in the following Equation 2.2, where $n-1$ and n are the ids of two subsequently received message and t_r is the time of reception.

$$CCP(n) = t_r(n) - t_r(n-1) \tag{2.2}$$

In the first instance, the CCP is only a metric for the relation of two individual received CAMs. It needs to be set into a statistical context for further evaluation. However, the evaluation of the simple arithmetic mean value $\mathrm{CCP_{avg}}$ will not always deliver the most interesting outcome. When a constant sending rate is assumed, the $\mathrm{CCP_{avg}}$ is directly related to the PDR and the frequency of sent messages f_s, as shown in the following example. The more significant result

MsgId	**Send.t**	**Recv1.t**	**Recv2.t**	**Recv1.ccp**	**Recv2.ccp**
0	*1,000 s*	*1,001 s*	*1,001 s*		
1	1,100 s	-	-	-	-
2	1,200 s	1,201 s	1,201 s	0,200 s	0,200 s
3	1,300 s	-	1,301 s	-	0,100 s
4	1,400 s	1,401 s	-	0,200 s	-
5	1,500 s	-	-	-	-
6	1,600 s	1,601 s	-	0,200 s	-
7	1,700 s	-	-	-	-
8	1,800 s	1,801 s	1,801 s	0,200 s	0,500 s
9	1,900 s	-	1,901 s	-	0,100 s
10	2,000 s	2,001 s	2,001 s	0,200 s	0,100 s

Table 2.1: Example of the sender and receiver message relation for an optimistic and realistic scenario with the same PDR

will be achieved by an evaluation of the $\mathrm{CCP}_{\mathrm{max}}$. The $\mathrm{CCP}_{\mathrm{max}}$ can serve as a direct measure for burst errors. Burst errors can be caused due to shadowing and fading properties on the radio channel or uncoordinated medium access and corresponding packet collisions. In turn, failed message delivery for longer time spans has the most considerable effect on the performance of V2X communication applications.

Table 2.1 gives an example of the communication relation between one sender and two receivers for individual messages and shows the characteristics of the CCP. In this example, the sender emits CAMs with a constant frequency of $f_s = 10\ Hz$. The receivers can either receive the CAM and then the time stamp of the reception is indicated; or miss the CAM. The transmission and processing delay from the sender to each receiver is assumed constant with the value of 1 ms. However, it is of minor importance for the evaluation. The message with id $n = 0$ is the starting reference message and received by both receivers. The following $M = 10$ sent messages are used for the evaluation. Even though, both receiver conditions are chosen synthetically for the sake of the explanation of the metric, both situations are possible. Both receivers experience the same PDR, which already has a rather low value of $PDR = 0.5$. Hence, each receiver can successfully receive 5 out of 10 sent messages. On the one hand Recv1 experiences steady conditions and can receive every second message. On the other hand Recv2 experiences a typical burst error situation, where it cannot receive messages for a longer period. The conditions can be compared with the optimistic case for Recv1 and the realistic case with 95% probability for Recv2 from Figure 2.2 (shaded rectangle).

The statistical evaluation of the $\mathrm{CCP}_{\mathrm{avg}}$

$$CCP_{avg} = avg(CCP(n)) = \frac{1}{N}\sum_{n=1}^{N} CCP(n) \tag{2.3}$$

yields the same result for both receivers Recv1 and Recv2.

$$CCP_{avg}(Recv1) = CCP_{avg}(Recv2) = 0.2\ s \tag{2.4}$$

As already explained before, the result depends directly on the PDR and the sending frequency $\mathrm{f_s}$.

$$CCP_{avg} = \frac{1}{PDR \cdot f_s} = \frac{1}{0.5 \cdot 10\frac{1}{s}} = 0.2\ s \tag{2.5}$$

As recently as the $\mathrm{CCP_{max}}$ is evaluated, the different receiving characteristics of Recv1 and Recv2 appear. With

$$\begin{aligned} CCP_{max} &= max(CCP(n)) \\ &= CCP(n_0)\,\{n_0 | \forall n : CCP(n_0) \geq CCP(n)\} \end{aligned} \tag{2.6}$$

the specific results for the example turn out different.

$$CCP_{max}(Recv1) = 0.2\ s \tag{2.7}$$

$$CCP_{max}(Recv2) = 0.5\ s \tag{2.8}$$

In this manner, the burst error in case of Recv2 can be clearly distinguished from the steady communication of Recv1.

Since the range of the CCP in general is determined by the sending frequency $\mathrm{f_s}$, the $\mathrm{CCP_{max}}$ would tend to $\frac{1}{f_s}$ in case of a perfect reception quality. In contrast, the $\mathrm{CCP_{max}}$ would tend to ∞ when the sender and the receiver are never in communication range. The intermediate values can arise due to a sender and a receiver being out of range anyway for a long term or due to a short term fading condition. This is why the CCP should always be evaluated in relation to the distance between the communicating nodes.

The CCP particularly qualifies for the assessment of safety related applications based on CAM communication with permanent message reporting. Hence, it covers nearly the half of the day one use cases from the ETSI basic set of applications. In literature, similar measurements are proposed under the synonyms of Inter Reception Time [EGH+06], Inter-Packet Gap, Update Delay [KGHS12], or Data Age [VLL15]. All in all, it confirms the relevance to evaluate V2X applications with metrics that regard for timely updates of periodic information.

The following section can introduce the communication architectures. These systems definitely have to accommodate applications with the different requirements, whereas the regular information refresh plays the most important role.

The second essential factor needs to consider an eligible communication range for the sender to reach the relevant neighbors in the vicinity.

2.3 Standardized Architectures

Several initiatives from the context of Intelligent Transportation Systems (ITS) addressed the realization of the driving-related safety and efficiency use cases. These initiatives were and are driven by various research projects with possibly different focus (e.g. on road safety, on communication infrastructure, on field operational tests). Furthermore, industry consortia and standardization bodies are involved in the process. As a result, several systems were developed and presented. Depending on the objectives of the initiative, the systems have a different grade of detail and also different architectures. Accordingly, harmonization activities are mandatory. The standardization arena comprises mainly three players. First, the technical committee TC 204 from the International Standardization Organization (ISO) works on the initiative named Communications Access for Land Mobiles (CALM) [ISO14]. This work is conducted together with the TC 278 at the CEN (European Committee for Standardization). Second, the IEEE as the world's leading professional association contributes the family of standards for the Wireless Access in Vehicular Environments (WAVE) [IEE14]. Third, the ETSI TC ITS together with the CEN accepted to work on the standardization related to the European Commission Mandate M/453 on Cooperative ITS. Moreover, the industry forum Car-2-Car Communication Consortium (C2C CC) works very closely together with the ETSI TC ITS [ETS13c].

Two different views are important in the standardization and specification of ITS. The first view regards the individual subsystems for the whole system. The subsystems connect with each other in a dedicated communication domain. The second view specifies the architecture of the subsystems. More precisely, the second view specifies the communication stack and the access to the communication domain to connect to the other subsystems.

2.3.1 Individual Subsystems

From top-level perspective, ITS consists of the following four individual subsystems or stations to enable especially road safety and traffic efficiency use cases [ETS10a].

The vehicle station is fixed onboard of one vehicle and enables the vehicle to participate in cooperative use cases. A vehicle station is not limited to a passenger car. It includes different vehicle classes depending on the construction (e.g. motorcycles or trucks) as well as the intention of use (emergency vehicles). A vehicle station comprises the Application Unit (AU) and the Communication and Control Unit (CCU). The AU runs the

ITS application and exchanges information with the CCU. Moreover, the AU has an interface to the driver, usually in form of a human-machine-interface (HMI), to accept input or present the ITS information. The CCU connects to the vehicles' sensor and actuator hardware, usually via the Controller Area Network (CAN bus). Furthermore, the CCU communicates to external ITS stations from possibly different types. The CCU provides information to the AU from the own sensors and the other subsystems and distributes information to the own vehicle controllers and the other subsystems. In a practical implementation, the car manufacturer develops the AU in-house and buys the CCU in addition from the suppliers. This way, the manufacturer can account for the unique selling proposition of its cars, especially with the HMI. However, according to standardization, the separation of AU and CCU on different hardware is not mandatory and open to the stakeholders. Due to the vehicle mobility, the communication domain towards the other subsystems always requires wireless access for any driving-related ITS use case. Certain vehicle-related use cases can also rely on wired communication access. For example a mobile device or a diagnosis device can connect via USB or Ethernet.

The roadside station also known as RoadSide Unit (RSU) or Intelligent Roadside Station (IRS), comprises the infrastructure components to operate a road. Roadside stations can be deployed at traffic lights, variable message signs or other fixed components at road sensors, construction sites etc. In contrast to the vehicles, the roadside stations always have a fixed position, at least for a dedicated amount of time, e.g. for the duration of the construction. Besides the exchange of sensor or traffic light information, roadside stations can act as a relay between vehicle stations to increase the communication range. Due to the fixed installation, roadside stations can be additionally equipped with a wired communication interface and act as a gateway to the wired data network, i.e. the Internet. In this way, roadside stations connect the wireless vehicle communication domain with the wired infrastructure domain, where the central stations are located.

The central station is an entity that runs centrally managed ITS applications and services. For example a traffic management center, a fleet management service center, or an advertisement company operate a central station. Central stations are usually servers in the Internet. For information exchange, the central station connects to the vehicle stations via two ways. The first way is the wired communication to the roadside stations, which forward the information with wireless access to the vehicle stations. The second way uses cellular communication infrastructure. This way also includes a wired part to the according cellular base station and the wireless part to the mobile user equipment in the vehicle station. The next Chapter 3 gives a detailed overview and comparison of the different communication technologies. Already now it should be noted that the communication via the infrastructure domain includes several forwarding hops, which induce an additional transmission delay. Due to this, time critical safety use cases are typically not realized with the participation of central stations. Rather, delay tolerant traffic efficiency or other location-based services make use of this kind of central subsystem.

The personal station represents a mobile consumer device, which is typically assigned to a person. Such a device can be a mobile phone or any other handheld device. These devices offer several communication interfaces and can serve for a variety of ITS applications. The personal station has a specific characteristic for different multimodal ITS scenarios, depending on the role of the person. A pedestrian or a cyclist can use the personal station as standalone unit. Moreover, the personal station can be connected to a vehicle station via e.g. Bluetooth or USB to extend the capabilities of the HMI and the communication interfaces. In this case, the personal station should be considered as a part of the vehicle station. Finally, personal stations may play an important role for the deployment of ITS. Since mobile phones are already very popular and widespread today, an according strategy to retrofit existing vehicles for personal station integration may accelerate the market penetration of communicating ITS participants. This would reduce the initial phase where customers perceive only minor benefits. Such an approach again highlights the need to think of ITS not only basing on a single communication technology, but on multiple ones to form heterogeneous vehicular networks.

2.3.2 ETSI TC ITS

The ETSI works on ITS standardization since 2007 and got input from several research projects as well as from other consortia. The COMeSafety project contributed with a specific support action [COM10] that got introduced in the ETSI standards. Amongst others, the European projects PRE-DRIVE C2X [PRE10], DRIVE C2X [DRI14] and the German project simTD [sim09b] for field operational test consulted during the preparation of the ETSI standardization. Furthermore, the Car-to-Car Communication Consortium also works close together with the ETSI. In addition to the previously introduced subsystem specification, the ETSI works in many areas to define ITS. The recently published technical report TR 101 067 - ITS Release 1 [ETS13c] bundles all current specifications on the topic.

As the group with the longest history in ITS standardization, the TC 204 at the ISO specifies the CALM standard. This work resulted in comprehensive set of published documents for the individual aspects of ITS. The architecture initially based on the CALM communication kernel to regard for CALM-aware applications - meaning ITS applications - and non-CALM-aware applications for general purpose applications. The additional CALM services layer provides functionalities that are shared between all applications. Moreover, the standard considers security aspects. In the original specification, the standard varies significantly from the ETSI TC ITS architecture. However, after a harmonization process the ISO published the latest release of the CALM architecture ISO 21217:2014 [ISO14], which adopts the same concept of the ITS station from the ETSI. The ISO document states that this "*edition cancels and replaces the first edition (ISO 21217:2010) which has been technically revised*" [ISO14].

In the manifesto from 2007 [CAR07], the C2C CC also addresses a layered communication stack with one part for C2C applications and one part for non C2C applications. Later on, the C2C CC fostered a very close cooperation with the standardization activities by the ETSI. This fact explains that the C2C CC architecture itself has not experienced any updates for a long time and lacks some important features that are state-of-the-art today.

Either effort from the ISO TC 204 as well as the C2C CC converges towards a harmonization with the ETSI TC ITS architecture. Meaning that this architecture turns out to be the future reference for ITS. Hence, it should be introduced in the following section. The major part of the ITS Release 1 accounts for the reference station architecture, specified in the European standard EN 302 665 [ETS10a]. The architecture is depicted in Figure 2.3. Each of the four presented ITS subsystems contains the functionality, described in this architecture.

Reference Architecture

The Application layer is the highest layer in the ITS station reference architecture. It contains the ITS applications according to the classification of road safety, traffic efficiency and other applications. The basic set of applications [ETS09] lists the envisioned ITS use case catalog. A management block and a security system accompany the main communication stack. Both blocks follow a cross layer design as management and security issues concern to all layers. The Facilities layer is an ITS specific concept [ETS13d]. Technically, it is a sublayer of the Application layer when set into relation to the OSI or the TCP/IP reference stack. Due to its importance, the Facilities layer is presented in closer detail in the next paragraph. The protocols on the Transport and Networking layers regard for ITS specific data (ITS Transport) and generic traffic (TCP and UDP). ITS specific traffic is characterized by relatively short data blocks. The Networking protocols already conform to the underlying access technology. As the application of ad hoc networks plays an important role in ITS communication, specifically tailored ad

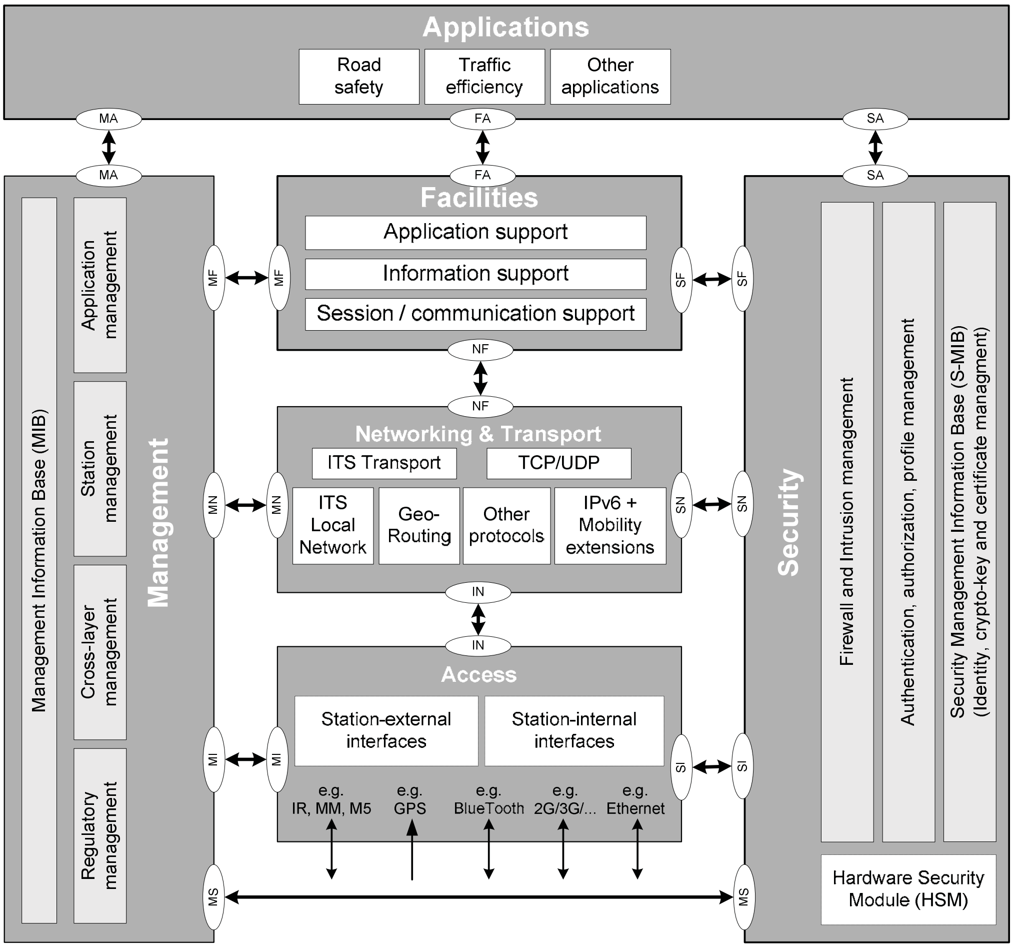


Figure 2.3: ITS station reference architecture by ETSI TC ITS [ETS10a]

hoc routing protocols can be found. For this purpose, GeoRouting protocols use the geographical position information of a station rather than topologies and IP addresses to route the data packets. Finally, the ITS reference architecture defines the possible access technologies. The access technologies allow the connection of personal stations and vehicle stations (e.g. via Bluetooth or Ethernet), the connection of station-internal interfaces for sensors (e.g. GPS) and station-external interfaces for external communication. The main ways for external communication are cellular access technologies (referenced as 2G/3G/...) and the ad hoc access technology via ETSI ITS G5. The G5 specification [ETS13a] defines the access in multiple channels in the allocated European frequency band for ITS in the range of 5.9 GHz and bases as the IEEE WAVE on the IEEE 802.11p standard. The two important communication principles towards external stations via ad hoc and cellular communication are presented in the next Chapter 3.

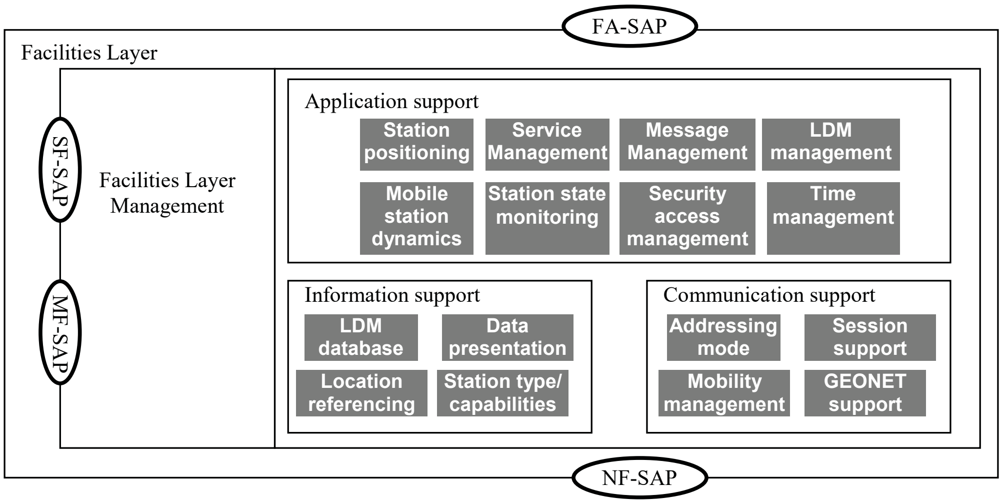


Figure 2.4: Functionalities of the ETSI TC ITS Facilities layer [ETS09]

Facilities

The Facilities layer provides different functionalities that can be shared between different applications and their assigned use cases. All currently identified applications are listed in [ETS09]. The functional requirements for the different facilities are listed in [ETS13d]. Figure 2.4 depicts the major facilities. The facilities are divided into the three different groups:

1. Application Support
2. Information Support
3. Communication Support

In general, facilities can either support applications or other facilities. The application support facilities on top account for the specific domains of ITS functionality. In turn, they use the information support and communication support facilities. Furthermore, several facilities may be applicable only to certain subsystems or even special types of stations.

Station Positioning This application support facility provides the positioning vector of the ITS station from available navigation system data (e.g. GPS, GLONASS). Certain use cases require a very high precision of the position, especially for vehicle stations. In this case, dead reckoning mechanisms improve the position accuracy by the fusion of positioning and additional odometry data, as the yaw velocity, the steering angle and others. For this purpose, the Station Positioning uses the information provided by the Mobile Station Dynamics facility.

Mobile Station Dynamics This application support facility is only applicable to vehicle stations. It maintains information about kinematic parameters from the odometer (e.g. the yaw velocity, the longitudinal and lateral acceleration, the stability control status and more) for applications as well as other facilities (e.g. the Station Positioning).

Station State Monitoring This application support facility is similar to the previous one. Analogical, it also monitors the state of parameters, in this case with static characteristics. At the example of a passenger car vehicle station, the wiper speed or light status are such parameters. Additional parameters for special vehicle stations may be supported. For example, an emergency vehicle also maintains the siren and light bar states.

Services Management This application support facility manages the service capabilities and related software updates of a station. Accordingly, this facility maintains the information to be shared with other stations in service announcement messages. The stations can identify whether certain (cooperative) use cases are possible by the use of service announcements.

LDM Management This application facility manages the continuous update of the Local Dynamic Map information. The LDM is a very important concept in ITS [ETS14c]. In brief, the LDM references gathered ITS information to a specific location on a digital road map. The information can be either received by internal sensors or by external stations via V2X communication. Beside the spatial attribute, ITS information also has a certain attribute for the time period to be valid. According to this time period, information can be static (the road network), semi static (landmarks for references), dynamic (road situations) or highly-dynamic (awareness data from the own sensors as well as surrounding vehicles).

Message Management This application support facility is responsible for generating, formatting, sending, and also receiving ITS application messages. Currently, two message types are of utmost importance. CAMs are sent permanently with a specific period to enable the essential information dissemination towards all vehicles in the surrounding [ETS14a]. DENMs are sent repeatedly within a limited time frame upon specific road events to signalize them [ETS14b]. The message management uses the services from nearly all other facilities for generating the content and determining the particular sending time of the ITS messages. For instance, ETSI rules define the CAM sending frequency depending on the change of the position, the heading and the speed for vehicle stations [ETS14a].

Security Access Management This application support facility provides an interface between the applications, the Facilities layer and the security entities. It enables the communication according to the appropriate security policy.

Time Management This application support facility maintains a global time reference that is used for all time stamped data elements in V2X messages as well as in applications.

Information Support These facilities provide the elements and processing methods for static and dynamic information that is used by the Facilities layer and accessed by the applications. It contains the LDM Data Base as repository for the LDM, the Location Referencing methods to associate the LDM content with a geographic position, the Data Representation of the CAM and DENM content, encoded according to the ASN.1 format, and the Station Type/Capabilities to register information about the station.

Communication Support This group of facilities provides the capabilities to manage various communication modes and sessions. It contains the Addressing Mode in connection with the GeoNet Support to determine the dissemination modes of messages, for ad hoc communication (e.g. unicast, broadcast or geocast in a certain geographic area) as well as cellular communication. Moreover, it provides the Session Support and Mobility Management for stations that are attached to the Internet.

Communication Paradigms

As aforementioned, the ETSI specification includes geographic networking and routing concepts to support the nature of safety and traffic efficiency use cases to address the vehicles in the local environment. Stations with georouting protocols maintain neighborhood tables that are continuously updated through beacon messages. When a station wants to send a packet to a geographic area, there are usually two modes. When the sender station itself is not located in the geographic area, it applies line forwarding. This means, it sends a unicast message to the neighbor, which has the shortest distance to the destined geographic area. Line forwarding is performed until the sender node is also located in the area. Then, area forwarding is applied. Area forwarding usually comprises a simple flooding, where every station again rebroadcasts the packet once. This packet-centric approach follows the conventional approach of packet switched communication networks. However, it may introduce a high channel load in certain situations with large geographic areas and many stations, also known as the broadcast storm problem. For instance, when many vehicles detect the end of a traffic jam and inform the following vehicles. As a consequence, congestion control mechanisms need to be applied to mitigate the problem [ETS11c].

One step ahead, the information-centric approach departs from the conventional forwarding semantic that resides on the networking layer [CAR07]. The information-centric approach bases on single hop broadcasting of all packets. At the receiver-side, the transport and networking layer passes the packets over to the facilities and application layer. The LDM in the facilities layer stores the incoming information and the processing logic in the application layer decides on further dissemination of the gathered information depending on the locational and temporal relevance [ETS11b]. This way allows improvements for the reduction of the amount of transmitted data towards several criteria. First, the advanced relevance and confidence checks by application algorithms can stop message forwarding when the information is out-of-date, out of the relevance area and so on. Second, in a case when each station receives multiple messages with similar content (e.g. from multiple other stations detecting the same situation), these multiple messages can be combined and redistributed as a single message. Summarizing and aggregation reduce the amount of data [HL10] by the application of statistical functions (e.g. the mean or maximum) for multiple values of a certain parameter. Summarizing simply combines the multiple values of the same parameter to build e.g. the average for the received velocities of the surrounding vehicles on one road segment. Aggregation goes one step further and can include hierarchical combinations to allow a gradual abstraction, for instance by the use of tree-structure representations. At the example of the average velocity per road segment, aggregation can regard near road segments individually and combine multiple distant road segments for further data reduction. In general, the information-centric approach implements a store-and-forward semantic for the information dissemination.

However, it is still an open question whether the pure information-centric approach outperforms the packet-centric approach in all situations. The information-centric approach is certainly more complex than the packet-centric approach as the higher layers need to be integrated in the routing process. The mechanisms in the facilities layer and the application layer induce an additional processing time to the information dissemination, which may violate the real-time constraints for certain use cases. For such use cases, hybrid concepts of the packet-centric and information-centric approach are recommended [CAR07]. For instance, a safety relevant and time-critical message can be disseminated via the packet-centric approach within the borders of a geographical area with immediate danger for the present vehicles. Beyond these borders, the message can be disseminated via the information-centric approach as it may be also of interest for informative and traffic efficiency reasons for distant vehicles. Such a hybrid approach could be useful in case of a hazardous location warning. The simulation analysis in Chapter 5 later in this thesis also addresses the issue of information-centric message dissemination and content aggregation.

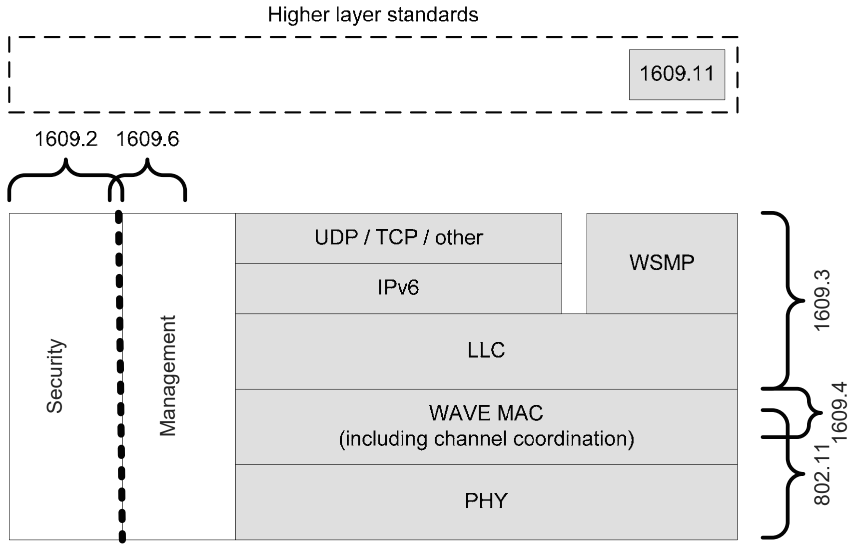


Figure 2.5: Architectural framework of the IEEE WAVE standards [IEE14]

2.3.3 IEEE WAVE

In the United States, ITS is strongly connected with radio spectrum and technologies known under the term Dedicated Short Range Communication (DSRC). The U.S. Federal Communications Commission (FCC) has allocated the radio spectrum to mobile services and the Society of Automotive Engineers (SAE) has defined messages to be used by applications for DSRC. The Vehicular Technology Society within the IEEE develops the radio communication system for Wireless Access in Vehicular Environments (WAVE). The outcome is the IEEE 1609 standard suite [IEE14], which in turn refers to the IEEE 802.11p WLAN standard [IEE10b]. IEEE 802.11p is an amendment to the 2007 revision [IEE07] and since 2012 incorporated in the complete revision [IEE16] of the well-known IEEE 802.11 family. It is especially designed for Wireless Access in Vehicular Environments. The architectural framework of the WAVE family is depicted in Figure 2.5.

The IEEE WAVE standard includes the pillars of the security and the management systems along the communication stack. The stack shows that the IEEE focuses more on the network technology than on the higher layers. The referenced IEEE 1609.11 standard on the application layer specifies an electronic payment protocol, e.g. for toll collection. Moreover, proprietary applications or SAE J2735 conform applications are intended. It is stated that "*further WAVE standards may be developed to specify higher layer, or application, features*" [IEE14]. On the Transport Layer, WAVE distinguishes between common transport protocols TCP/UDP over IP, or the WSMP. The Wave Short Message Protocol accommodates the typical characteristics of M2M-communication that messages are rather short, but need to be sent more frequently. Similar to the ETSI TC ITS standard, this architecture aims for the support of the three V2X application categories of safety and efficiency as well as infotainment applications. However, the most important parts of this architecture regard to the comprehensive specification of the MAC and PHY layer. In contrast to the other architectures, WAVE only specifies one access technology according to IEEE 802.11p. However, 802.11p access is the de facto solutions for ad hoc communication between vehicles. The IEEE 802.11p standard for general ad hoc communication will be referenced again in the next Chapter 3.2 when it comes to closer details about the communication technologies.

The IEEE 1609.4 part [IEE11] specifies an important extension to the IEEE 802.11p MAC layer for multi-channel operations. It introduces the channel routing entity, which uses one dedicated MAC sublayer entity from IEEE 802.11p for each channel. The channel routing directs messages from the upper LLC layer to the designated channel and sets the according parameters (e.g. for transmission power). For instance, the US as well as the European spectrum definition contains up to seven channels for V2X communication in the band around 5.9 GHz. More specifically, ETSI ITS [ETS13a] defines one CCH (Control Channel) and two SCHs (Service Channels) in the ITS-G5A band and additional 4 SCHs in further G5 bands. Multichannel operation intends primarily to support safety critical communication in the separate CCH and non-safety communication in the SCHs to avoid interferences between these message classes. The general concept of the IEEE 1609.4 bases on a time division scheme for the channel switching. According to this, time based on UTC (Coordinated Universal Time) is separated into Sync intervals of 100 ms. One Sync interval comprises one CCH interval followed by one SCH interval, which are 50 ms each. A further guard interval at the beginning of each channel interval (CCH interval or SCH interval) accounts for robust switching between the channels. The guard interval consists of the Sync_tolerance of 2 ms and the Max_Ch_Switch_time also of 2 ms. The Sync_tolerance describes the differences of the internal clocks of the stations towards UTC. The Max_Ch_Switch_time represents the time for tuning the radio hardware to the other channel. During the guard interval, no transmission is allowed.

Figure 2.6 illustrates the different options for the channel access. These methods are in the first instance specified for stations with a single-radio device. A dedicated access option may be used only for certain time span. Typically, the continuous and alternating access will take turns when the situation demands the according option. The immediate - and extended access are additional options.

Continuous access requires no channel coordination. The station tunes all the time to one dedicated channel. Basically, it is envisioned that the station permanently uses the CCH to take part in applications with safety-critical communication.

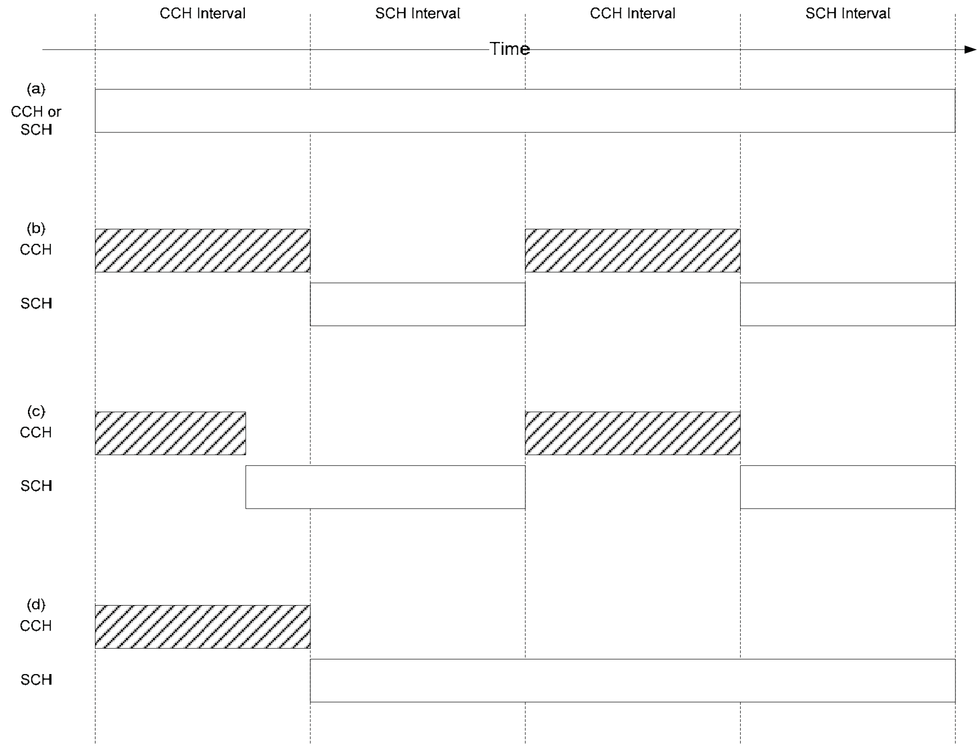


Figure 2.6: Channel access options according to [IEE11]: (a) continuous, (b) alternating, (c) immediate, and (d) extended

Alternating access is the case for multichannel operation when a station is (temporarily) engaged in applications with non-safety communication, which is processed over the SCH. It allows the station to access the CCH during the time frame of the CCH interval and switch to one SCH during the SCH interval to access the service.

Immediate access “*allows immediate communication access to the SCH without waiting for the next SCH interval*” [IEE11].

Extended access “*allows communication access to the SCH without pauses for CCH access*” [IEE11].

A general problem of the time division approach is that a station may miss important messages transmitted on the CCH, while it has tuned to the SCH. The additional options for immediate and extended access reduce the time for safety-critical communication. However, certain drawbacks of the communication performance were also reported for the alternating access [CJD09, HKRL10].

The clearest issue with IEEE 1609.4 arises due to inefficient channel utilization [CJD09]. Basically always when stations are engaged in multiple applications with safety-critical and non-safety communication and switch between the CCH and SCH, all other stations in the neighborhood that stay on the CCH for the whole time may be forced to limit their communication to the CCH interval. Only this way allows ensuring that important safety-critical messages are not lost for the switching stations. Moreover, the needed guard interval reduces the effective time span when safety-critical messages can be communicated to less than the half of the available time. The second issue arises due to the queued safety messages during the SCH interval. At the start of the CCH interval, the according sending attempts of these messages increase the probability of message collisions. The medium access procedures of IEEE 802.11p are presented in closer detail in the next Chapter 3.2. However, already now, it can be stated that the uneven concentration of sending attempts decreases the communication performance. A third issue is the missing migration path towards stations with multi-radio devices.

The co-existent deployment of single-radio and multi-radio stations will impair the capabilities of the multi-radio stations as they need to limit their safety-critical communication to the CCH interval [HKRL10]. A proposed multichannel safety approach with an intentional bit to signal the channel switching improves the performance for the case of a continuous CCH for a certain time span [HKRL10]. Still, the best performance would be achieved with a dedicated safety radio approach. Single-radio stations would always use the CCH for communication. Multi-radio stations would tune one radio always to the CCH and could use the other radio to switch between the SCHs according to the used services. From protocol design, this approach is also favorable due to its simplicity.

2.4 Summary of System Overview

This chapter introduced the different groups of applications and presented the most prominent architectures to realize the V2X communication system. The major part of safety and efficiency applications bases on a characteristic M2M communication pattern with periodic message exchange to inform the neighbors in the vicinity. Main aspects to distinguish the applications include the duration and mobility of a situation to be informed as well as the possible number of reporters. From this follow different communication range and timing constraints. The CCP is a suitable metric to measure these requirements. From the existing systems, especially the ETSI TC ITS reference architecture accounts for the diversity of applications. With the Facilities Layer, it specifies several valuable utilities. For instance, the LDM introduces a concept to enable applications with less critical timing requirements but an extended horizon. The IEEE WAVE architecture defines one particular access technology. Nonetheless, it also aims to support different application requirements, e.g. with the multi-channel design. In this way, applications with different constraints regarding latency and communication range could be separated on different channels. The main objective of this thesis goes one step further and proposes to separate different applications not only on different channels, but even on different access technologies. The next Chapter 3 will present a detailed discussion about the two major concepts of ad hoc and cellular systems. These technologies will be briefly evaluated on a theoretical basis with the help of the CCP. Later, Chapter 5 will analyze the communication exchange by simulation. The applications will implement the relevant features like the ETSI facilities and communicate according to the presented pattern of regular updates, which was the basis of most safety and efficiency use cases.

Chapter 3

Communication Technologies

The first section of this chapter presents the fundamental characteristics of the radio channel to provide a basis for the later description of the communication technologies themselves. Second, the ad hoc communication mode according to the IEEE 802.11p standard is presented and important amendments are introduced. Third, the different cellular families of UMTS and LTE, specified by the 3GPP, are introduced in the cellular communication networks section.

3.1 Radio Channel

The radio channel is a physical transmission medium with particularly challenging characteristics. The fundamental transmission principle of the radio channel is described by the propagation of the electromagnetic waves through the open space [Max73]. The information reception in the radio channel relies on the successful distinction of the signal from the noise [Sha48], as in all communication systems based on electromagnetic waves - so in guided wired media. However, the open space transmission leads to multipath propagation and time variation of the channel [HM04]. Multiple paths arise by the phenomena of reflection, diffraction or scattering of the electromagnetic waves on the objects, also known as the scatterers, in the environment of the transmitter and receiver. The channel properties vary over time due to the mobility of all objects - including the communicating nodes. The relation of the scatterers and the phenomena is displayed in Figure 3.1. The figure includes two additional paths. The **Line-Of-Sight** (LOS) path is the direct path between the transmitter and the receiver. It does not experience any deflections from the scatterers and arrives at the receiver with the shortest delay and the highest amplitude. In contrast, the **Shadowed** path is deflected in such a way that it never reaches the receiver at all.

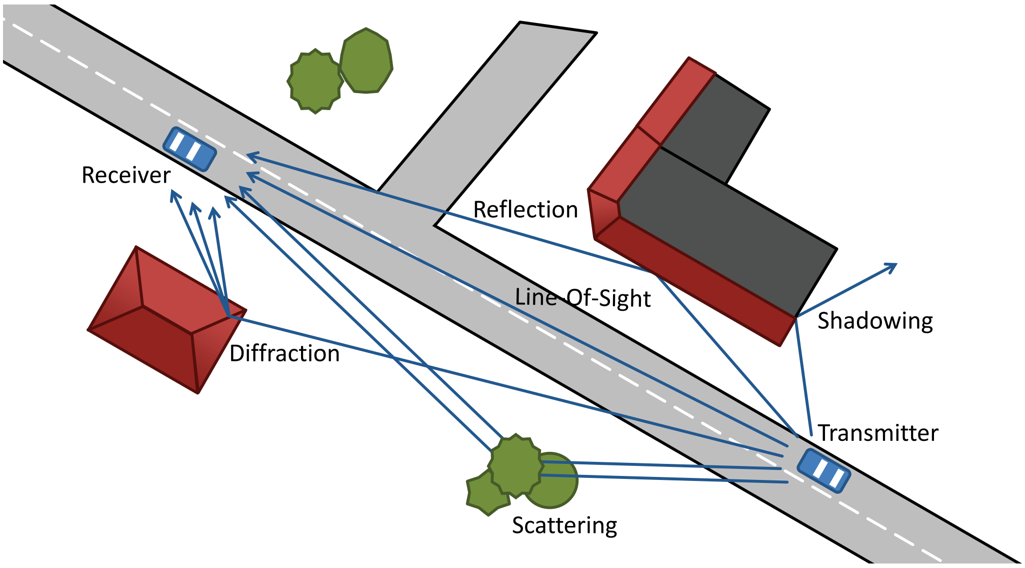


Figure 3.1: Multipath propagation scenario in the vehicular environment

Reflection occurs when the radio wave hits a plane surface. In this context, plane means that the surface has large dimensions compared to the wavelength of the signal. According to Snell's Law the emergent angle is proportional to the incident angle. Reflection commonly takes place on big objects as vehicles or walls of buildings. In case of reflection, not the complete energy of the wave emerges again, but a part enters the material of the surface. This characteristic is denoted as **Penetration**.

Scattering is a special case of reflection. It exists when the wave hits a rough surface or one with small dimensions, such as leaves of plants. In this case, multiple reflections superpose to an emergent wave with an angle that is orthogonal to the surface [HM04]. The smoothness (resulting in reflection) or roughness (resulting in scattering) of the surface is described by the Rayleigh criterion in Equation (3.1). The surface is smooth, when the deviation of the surface σ_s

$$\sigma_s < \frac{\lambda}{8 \cos \alpha_i} \tag{3.1}$$

Where λ is the wavelength of the radio signal and α_i is the incident angle.

Diffraction takes place when the wave is refracted on a sharp edge. According to the Huygens principle, a new wave front emerges at the point of incident of the primal wave. Diffraction occurs for instance on corners of buildings.

At receiver side, the partial waves with different amplitudes, delays and phases superpose to combine one arriving signal. Each path has an according power delay profile. The channel impulse response h in Equation (3.2) describes this process as the sum of Dirac delta impulses of different amplitude a_i, phase shift θ_i and delay τ_i from the ith multipath [Rap02]. The time difference between the shortest (earliest) and the latest path is referred to as maximum excess delay.

$$h(\tau) = \sum_{i=1}^{N} a_i e^{j\theta_i} \delta(\tau - \tau_i) \tag{3.2}$$

The amplitude of the radio signal at the receiver side, also written as P_r, depends on the transmission power P_t and the **Path Loss** L_p for each one of the multiple paths (with $P_r = L_p P_t$). The path loss describes the decrease of the amplitude of the radio wave during the transmission. The amplitude can particularly decrease for any deflection of the wave, when a part of the energy penetrates a surface. However, the amplitude also decreases during the propagation through the free space. According to Equation (3.3), the freespace path loss L_{fs} is proportional to the frequency of the radio wave (reciprocal to the wavelength λ) and also depends on the distance d from the transmitter [Fri46]. The decibel notation on the right side of Equation (3.3) is a typical notation for derived radio propagation models.

$$L_{fs} = \left(\frac{4\pi d}{\lambda}\right)^2 \leftrightarrow L_{fs}[dB] = 2 \cdot 10log\left(\frac{4\pi d}{\lambda}\right) \tag{3.3}$$

Therefore, communication systems at a higher carrier frequency exhibit a higher path loss. The amplitude decreases with higher distances until it is not capable of being differentiated from the noise floor. Additionally, the constructive and destructive superposition of the partial waves leads to fading with significant effects. Fading can be divided into large scale and small scale fading. Large scale fading mainly arises due to large shadowing objects. Small scale fading occurs due to small movements of the communicating nodes and the scatterers in the environment.

The effects of fading attribute to the dispersion of the radio signal. For the radio channel, two kinds of dispersion exist - time dispersion and frequency dispersion [Rap02]. Dispersion is generally known as the dependency of a physical variable on the wavelength. In optics, it would be the wavelength of light. For the radio channel, it is the wavelength of the transmitted radio waves. The principle of dispersion can be well explained with a basic concept of the information transmission. The information signal commonly gets modulated on a sinusoidal carrier wave at a certain frequency. Multiple carrier waves are arranged adjacently in the frequency spectrum, according to national frequency plans. Figure 3.2 depicts such a spectrum setup. Additionally, it includes a time component to account for subsequent transmission of the carriers. Even though, newer radio air interfaces as WCDMA and OFDMA apply a slightly different concept than the

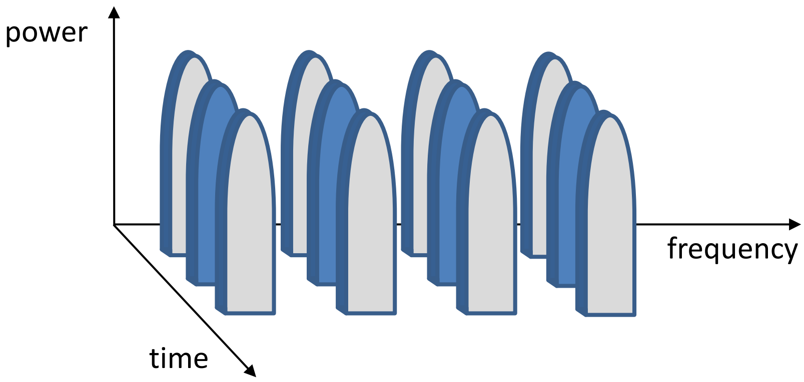


Figure 3.2: Simplified multicarrier spectrum allocation

sinusoidal carriers (as explained later), the simplified model serves well for the explanation of dispersion.

First, **Time Dispersion** is the shift and spread of the modulated data signal along the time. It is a result of the frequency selective properties of radio channel, which are in turn caused by the multipath phenomena of the wave propagation. Frequency selectivity means that signal parts of different frequencies experience different changes through the channel. For instance, the occurrence of reflection versus scattering at a given surface according to the Rayleigh scattering criterion in Equation (3.1) depends on the wavelength of the incident wave. Reflection leads to different behavior of the emergent wave compared to scattering. The important measure to characterize if the existence of time dispersion has a disturbing effect is the coherence bandwidth. The coherence bandwidth specifies the part of the frequency band where the behavior of all frequency components can be assumed as equal over the time. If a modulated signal occupies a larger bandwidth than the coherence bandwidth, the time dispersion delays different frequencies of a signal differently. In other words, the channel impulse response from Equation (3.2) has multiple versions of that signal with different attenuations at different delays. The resulting interference effect is commonly referred to as Inter Symbol Interference (ISI). As a general rule, broadband radio systems are more vulnerable to the disturbance of time dispersion than narrowband systems. The described context is named and modeled as frequency selective fading [Rap02].

The second dispersion of radio channel is the **Frequency Dispersion**. It is the result of relative mobility of communicating participants and obstacles and connected with the Doppler Effect [HM04]. The Doppler Effect causes a shift or spread of frequency components of the signal. The analogous measure is the coherence time, which specifies the time span where the channel can be assumed as constant. The coherence time depends on the length of the radio wave and also on the relative speed of the communicating nodes. A high coherence time means that the channel changes less often and stays constant for longer periods. This behavior is referred to as slow fading. If the coherence time is smaller than the symbol rate, it is possible that the channel conditions change within one symbol period. This effect is called fast fading. Fast fading can lead to deep fades for short periods of time, where the information signal cannot be sensed at all.

As a consequence of the described characteristics, the radio channel exhibits rather adverse prerequisites for successful information transmission. Moreover, there is no way for improving the medium itself as it is in wired media with cable shielding, impedance balancing or line termination. In fact, the Bit Error Rate (BER) of the communication systems based on copper or fiber is in the order of 10^{-12} to 10^{-15}, while the wireless channel achieves merely 10^{-3}. Another important difference to wired systems arise of the fact that the radio channel "*has neither absolute nor readily observable boundaries*" and is therefore "*unprotected from other signals that are sharing the medium*" [IEE16]. This aspect is especially important when the access of multiple nodes to the medium needs to be regarded. On this account, two categories of channel access methods play an important role in the design of wireless systems. Scheduled channel access methods based on multiplexing usually need a central coordination instance. In the cellular systems, the infrastructure components as base stations control the transmission to prevent message collisions. Cellular systems are presented in Section 3.3. In decentralized systems, every node itself applies access methods that base on contention. The next Section 3.2 about ad hoc communication addresses this kind of system.

3.2 Ad Hoc Communication

From the beginning, vehicular communication networks are considered as a special type of wireless local networks with moving vehicles and fixed RSUs communicating in an ad hoc fashion. Hence, the term VANET is still a prominent synonym. The technical basis for VANETs is formed by the IEEE 802.11 WLAN standard family. The IEEE 802.11p amendment particularly regards for vehicular environments [IEE10b].

3.2.1 IEEE 802.11p

The main content of the IEEE 802.11 standard covers medium access procedures (MAC) and physical layer signaling techniques (PHY) for wireless local networks. Moreover, it defines the operation at different frequency bands, the spectrum.

Spectrum

IEEE 802.11p operates in the frequency bands around 5.9 GHz. More specifically, in Europe the spectrum of 5.855 - 5.925 GHz is available. The FCC in the US

Parameter	20 MHz channel (11a)	10 MHz channel (11p)
No. data subcarriers	52	52
No. pilot subcarriers	4	4
Modulation	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM
Coding Rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4
Symbol duration	4 μs	8 μs
Guard interval	0.8 μs	1.6 μs
FFT period	3.2 μs	6.4 μs
Preamble duration	16 μs	32 μs
Subcarrier spacing	0.3125 MHz	0.15625 MHz
Bit rate	6, 9, 12, 18, 24, 36, 48, 54 MBit/s	3, 4.5, 6, 9, 12, 18, 24, 27 MBits/s

Table 3.1: Comparison of the Physical Layer parameters of IEEE 802.11a and IEEE 802.11p ([IEE07])

has assigned the band 5.850 - 5.925 GHz for vehicular communication.

PHY

The latest revision of the IEEE 802.11 standard [IEE16] maintains two different groups of physical layer modulation schemes. The legacy system originally defines a spread spectrum technique, still applied in 11b. According to Figure 3.2 from the previous section, spread spectrum uses only one single-carrier for the modulation, but spreads the information over the whole bandwidth. This scheme is now superseded by Orthogonal Frequency Division Multiplex (OFDM), which is originally introduced with the line of 11a and commonly used today for all consumer WLAN standards as 11g, 11n, 11ac and more. The IEEE 802.11p employs exactly the same physical layer. According to Figure 3.2, OFDM modulates the signal on numerous subcarriers in the frequency band. The individual subcarriers are arranged in a very close manner. The center frequency of each subcarrier is placed at the single frequency where the oscillations of the other subcarriers are at their zero point [SL05].

The employed OFDM in IEEE 802.11 divides the given frequency band into 64 subcarriers, whereas each 6 subcarriers at the boundaries of the assigned band are left unused. From the remaining 52 subcarriers, 48 carry the information signal and 4 are used as pilot carriers to support channel estimation techniques. One OFDM signal can be seen as multiple narrowband signals. In this way, it is already very robust against frequency selective fading. Still, the high relative movement speeds in vehicular environments lead to frequency dispersive channels in connection with the Doppler Effect. For this reason, IEEE 802.11p specifies expanded timing parameters to countervail the arising fast fading properties. Therefore, the standard defines the half-clocked operation. In contrast to the regular operation, the half-clocked mode uses only the half of the channel spacing of 10 MHz, with the result of doubled timing parameters. The doubled symbol duration and particularly the doubled guard interval ensure a more robust signal. Table 3.1 summarizes the most important properties of the half-clocked 10 MHz channel of 11p in comparison to the regular 20 MHz channel as for instance employed in 11a. As a consequence, the half-clocked operation in 11p improves the signal robustness at the prize of the halved bit rate for the data payload. The assigned spectrum in Europe of 5.855 - 5.925 GHz accommodates seven 10 MHz channels for multichannel access.

MAC

Besides the PHY layer specification, the MAC layer is the other important part of the IEEE 802.11 standard. Three different access scheduling mechanisms are defined.

- Point Coordination Function (PCF)
- Distributed Coordination Function (DCF)
- Hybrid Coordination Function (HCF)

The PCF is employed when a central instance like a wireless Access Point (AP) coordinates the communication. It is not of interest for vehicular communication. The more important function is the DCF as protocol for access scheduling in ad hoc networks. The HCF is a new coordination function that supports two enhanced channel access methods. It is introduced to the IEEE 802.11 family with the 11e standard. While HCF Controlled Channel Access (HCCA) works a similar to the PCF, the Enhanced Distributed Channel Access (EDCA) is a variant of the DCF to incorporate Quality of Service (QoS).

DCF and EDCA use a form of the Carrier Sense Multiple Access mechanism with Collision Avoidance (CSMA/CA). In other words, each station employs the "listen before talk" principle for every packet transmission. IEEE 802.11 supports unicast as well as broadcast communication. For unicast communication with one dedicated addressee, each packet can be acknowledged with an ACK control packet upon successful reception. Otherwise, the packet can be considered as lost and as a consequence being retransmitted. Moreover, sender and receiver can virtually reserve a free communication slot with the request-to-send / clear-to-send (RTS/CTS) hand shake. However, these mechanisms are not possible or reasonable for broadcast communication with multiple receivers of a possibly unknown number. In the case of an unknown number of receivers, the sender would not

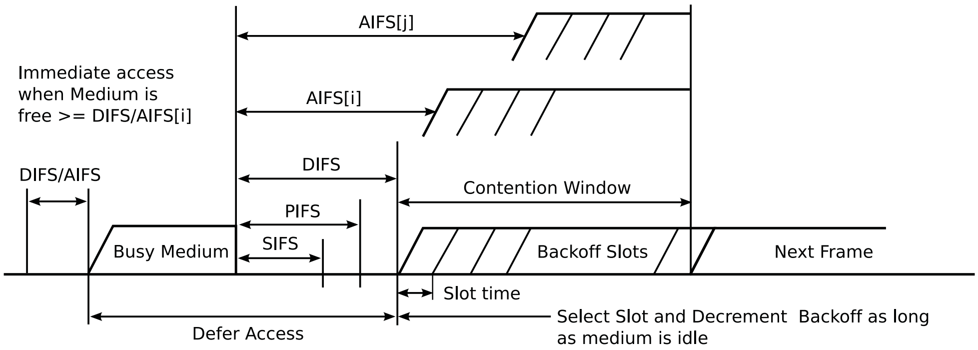


Figure 3.3: IFS relationships for IEEE 802.11 access timing ([IEE16])

know how many ACKs it has to await to consider the packet as successfully sent. In other cases, control overhead would increase dramatically. Due to this, no further control signaling is employed for broadcast communication, at the chance of packet losses. Obviously, the broadcast operation is the most interesting one for typical V2X communication use cases [PRE08].

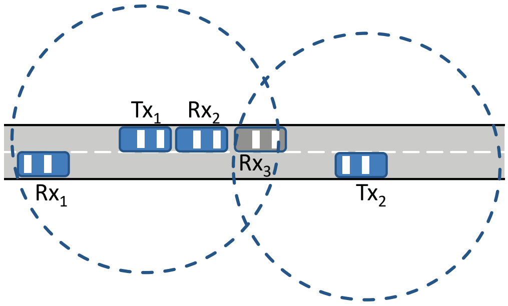
The procedure for the channel access is explained best with the timing sequence in Figure 3.3, which is extracted from the standard [IEE16]. Now, when a station wants to transmit a packet, it first has to sense the medium to get the current occupation state. If the radio channel is free at this point and for a time span of the DCF Interframe Space (DIFS), the station can immediately proceed with its transmission. To determine the medium as idle or busy, the station compares the measured signal energy from the antenna with the carrier sense threshold in the clear channel assessment (CS/CCA). The CCA threshold can be configured to implement a more sensitive or more aggressive behavior. With a low CCA threshold, stations will listen for ongoing transmissions in the further vicinity.

If the channel is already occupied at the time of initial the sending attempt, the station has to wait as long as the channel is busy to avoid interfering the current packet. After the channel becomes idle again for the time of DIFS, the station needs to execute an additional backoff procedure to defer the transmission for a random time. The random backoff procedure is necessary as also other stations may wait for the end of an ongoing transmission. An immediate transmission after DIFS would result in simultaneous sending attempts of all waiting stations, which basically leads to packet collisions at the receivers. For the backoff procedure, each station selects a random value in the interval between [0, CW], where CW is the contention window. While the channel is free, the station decrements the backoff value by one for every backoff slot. After the backoff value is counted to zero, the station can transmit its packet. When the channel becomes busy within this time, it can be assumed that another station has chosen a smaller backoff value. Hence, the station needs to suspend the countdown and resumes when the medium is idle again for time of the DIFS. In general, the size of CW can be configured to balance a high channel utilization at a small the number of collisions. A smaller CW increases the probability that two stations select the same backoff value and cause a packet collision due to simultaneous transmission, whereas a higher CW reduces the actual channel utilization time as stations defer their transmission for longer time. The DCF specifies an initial CWmin, which is increased with every packet collision up to a CWmax. For instance, the CWmin for broadcast operation is 15 slots, whereas each slot has the length of 13 μs.

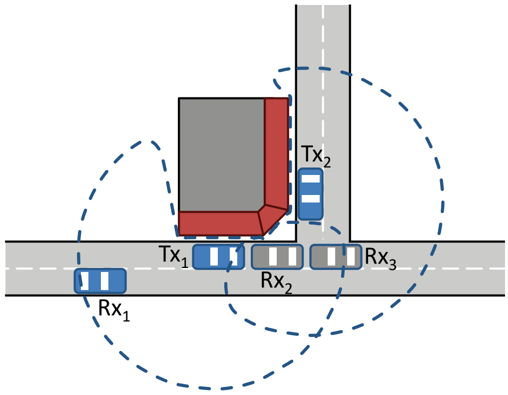
EDCA extends the DCF to incorporate QoS, mainly by prioritization of certain packets. The IEEE 802.11e EDCA defines four different levels of priorities, called access categories (AC), for Background, Best effort, Video, and Voice. Each AC owns a specific configuration of the CWmin, CWmax values as well as the AIFSN value. The AIFSN value is used to calculate the Arbitration Interframe Space (AIFS), which replaces DIFS for the channel sensing (see Figure 3.3). Through the configuration of a small AIFSN and a small CW, the station takes less time for channel sensing and possibly selects a smaller backoff value. Consequently, the probability for earlier channel access increases. In the 11e ACs, Voice has the highest priority meaning the smallest values for the AIFSN, CW configuration before Video, Best effort and Background with the lowest priority. Even though these ACs do not exactly map to V2X communication use cases, the priority configuration of different packets is reasonable as well. For instance, periodic awareness messages could be sent at the AC configuration of Best effort, while very safety-critical event-based messages should be prioritized with Voice or Video timings.

For the sake of completeness, the Figure 3.3 includes two further IFS, which are not relevant for broadcast communication. The SIFS is the Short Interframe Space and shall be used prior to the transmission of control frames as the ACK or CTS. The PIFS is the PCF Interframe space and is used when a station operates under the PCF in the infrastructure mode [IEE16].

Besides the selection of the same backoff value, the other major issue for simultaneous access and packet collisions arises due to uncertain channel sensing. An appropriate length of DIFS or AIFS can avoid sensing during fast fading outages. Still, nodes being out of communication range are not accounted. The Hidden Terminal Problem [TK75], which is also referred to as the Hidden Node Problem describes this issue. Figure 3.4 depicts two scenarios where this problem occurs. Assume a broadcast transmission is ongoing from transmitter Tx_1 to all nodes in its range (the dashed circle). In the same moment, Tx_2 also makes an attempt to send a packet and executes the DCF/EDCA access procedure. Since Tx_1 and Tx_2 are not in range of each other in these scenarios, Tx_2 would determine the radio channel as free and would start its transmission. At the receivers in the overlapping range of Tx_1 and Tx_2, the packet of Tx_2 increases the



(a) Rural



(b) Urban

Figure 3.4: The Hidden Terminal Problem in different scenarios

interference term of the SNIR. When the signal from Tx_1 is not significantly higher than the signal from Tx_2, both packets cannot be decoded and get lost. The Hidden Terminal Problem is considered to reduce the communication performance dramatically [TK75]. Indeed, in an AP based topology where all communication goes through the AP, it leads to a major degradation. In decentralized networks as VANETs, primarily the communication range decreases. In the Rural scenario without scatterers in the vicinity, only Rx_3 is concerned of a collision and not able to receive the packet from Tx_1 (Figure 3.4a). However, as a result of the presented radio propagation effects, hidden terminals can appear much closer. Due to shadowing in the Urban scenario, Rx_2 and Rx_3 are affected by a collision, whereas the distant Rx_1 receives the packet from Tx_1 (Figure 3.4b). In practice, the number of collisions caused by the Hidden Terminal Problem depends on the number of nodes and their location, the propagation environment, the transmission power, and also the amount of transmitted data.

The solution to the Hidden Terminal Problem is the already mentioned RTS/CTS handshake. For AP based topologies or in general for unicast communication, this solution is usually employed. However, for broadcast communication with multiple receivers - as the case for V2X communication - it is not applicable.

Consequently, the CSMA/CA based medium access is regarded to exhibit reliability problems for real-time communication, especially in situations with a high channel load [BUS10, SBL+11]. In this case, high packet losses and high medium access delays can occur. The adjustment of the CCA threshold for channel sensing can mitigate the problem [SBL+11]. However, alternative time slotted access approaches promise to outperform the random approach from CSMA/CA. Next section briefly introduces the two candidates.

3.2.2 Alternative Access

Self-Organizing Time Division Multiple Access (STDMA) [BUS10] and Mobile Slotted Aloha (MS-Aloha) [CSCB09] are not only presented on academic basis, but also investigated for applicability for V2X communication by a working group of the ETSI ITS TC [ETS11a, ETS12].

STDMA is already in commercial use for communication between ships in the Automatic Identification System (AIS). In AIS, ships are required to regularly transmit their position information for localization. This concept is similar to exchange of periodic messages that should provide cooperative awareness in V2X communication use cases. For access scheduling, STDMA divides the time into frames and further into a fixed number of time slots with a fixed duration. For instance, in AIS, a frame has a duration of 60 s and starts with every new minute according to UTC. Each time slot is dimensioned in the way to accommodate one packet. A node (i.e. a ship) that wants to take part in the communication performs the following procedure [BUS10]. After initialization in the network, the node listens to the radio channel for the duration of one frame and determines the current slot occupation. With the heartbeat rate of the own messages and the frame duration, the node calculates the nominal increment of time slots between each heartbeat. Afterwards, the node draws a random selection interval of slots from which it reserves a free slot for the own transmission. If no slots are free in the selection interval, the node reuses the slot that is already reserved by the node the furthest away from itself. This procedure is performed for each nominal increment in the frame. To account for network changes - e.g. due to node mobility - each node reapplies the reservation mechanism after 3 to 8 frames.

Similar to CSMA/CA, STDMA employs a self-organizing protocol without overhead for control information. In high load situations without free transmission slots, STDMA still facilitates the transmission to nodes in the close vicinity at the price of collisions at distant nodes. Especially for V2X communication use cases, this is regarded as fair, as the regular information updates on the proximate situation are an important object. In high load scenarios, STDMA performs better compared to the DCF-based MAC for the packet reception of close nodes and the channel access delay [ETS12]. Moreover, the channel access delay in STDMA exhibits a deterministic upper bound in contrast to the random delay in the DCF.

As the name says, MS-Aloha also bases on time division into frames and slots. It extends the latest version of the Reliable Reservation Aloha scheme (RR-Aloha+) to manage mobility issues [CSCB09]. As the main principle in the MS-Aloha protocol, every transmitting node appends the Frame Information (FI) to each transmitted data packet. Amongst other information, FI contains the status for each slot in the frame as perceived by the node. The status can be busy, free or collision. In the case of a collision, the slot is free for usage in the next frame. With the own channel sensing and the received FIs from the other nodes, each node obtains a diversified perception of the channel state for the according time slots. With the feedback from the other nodes in their FIs, MS-Aloha is even able to mitigate the Hidden Terminal Problem and unintentional collisions. Still, MS-Aloha allows intentional collision mechanisms when all slots are reserved. To reuse a slot for the own transmission, a node can ignore the busy indication of one slot when the received power falls below a certain threshold. Similar to STDMA, this approach prefers the transmission to nodes in the proximity, while increasing the collision probability at distant nodes. Moreover, MS-Aloha supports preemption, which is managed through the priority state field in the FI. For an own high-priority transmission, a node can initiate a collision in a busy slot at lower priority to claim the slot for itself in the next frame.

With a limited amount of control information, MS-Aloha introduces several suitable features. Similar to STDMA, MS-Aloha supports deterministic channel access to meet the real-time requirements of V2X communication use cases [ETS12]. With the use of the FI, MS-Aloha includes a decentralized handshake mechanism to mitigate the Hidden Terminal Problem. Especially in urban scenarios with shadowing characteristics (as in Figure 3.4b), it can yield excellent results [CSCB09]. Finally, the preemption mechanism provides scalable access for different priority levels of data traffic.

Even though the first simulative investigations on the time slotted approaches delivered promising results, there are also some concerns about the drawbacks. First, the reservation of time slots can also turn into a problem of increased packet collisions. Especially, due to the high mobility and frequent topology changes, nodes may get into communication or interference range and slot states get outdated. Even the feedback information in FI cannot prevent collisions, but only inform the nodes for the upcoming frame. Second, the time slotted approaches assume that all packets need to have the same length and each packet needs to fit into one slot. This limits the flexibility and may lead to a waste of the channel resources for packets with varying lengths. Third, a very practical issue arises due to the requirement of time synchronization between all nodes. In the real world, the local clocks will always exhibit uncertainties and misalignment towards the other nodes. Moreover, the frame structure needs to consider propagation delays for different distances between the nodes. As a solution to these two issue, an adequate guard interval between two consecutive slots needs to be introduced [ETS11a]. Such a guard interval will probably have an impact on the communication performance.

In summary, the time slotted access approaches offer an interesting alternative to the CSMA/CA mechanism. However, due to several open questions regarding the definite design of the alternative protocols, further investigations in this thesis will keep with the standardized IEEE 802.11 specification.

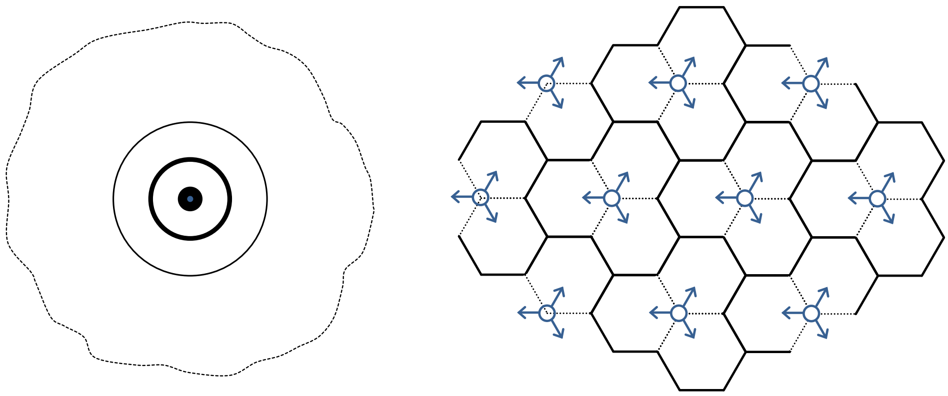


Figure 3.5: Typical structure of a cellular network compared to a single unidirectional transmitter

3.3 Cellular Communication Networks

3.3.1 System Architecture

Cellular systems originated for the setup of mobile phone networks. In contrast to a single unidirectional transmitter, cellular networks cover a larger geographic area by multiple cells of a smaller communication range [Gar07]. Figure 3.5 compares both principles. According to the current state of the art, a Base Station (BS) uses three antennas to control three sectors, where each of which spans an arc of 120 degrees [Gar07]. This work uses the definition that one sector conforms to one cell, meaning that one BS controls three cells. The mobile user communicates with the User Equipment device (UE) via the radio channel with one antenna of a certain BS. As in ad hoc networks, the communication signal decreases with higher distances between the BS and the UE. When the UE moves away from its connected BS-antenna, there is a point, where it is better to handover to another antenna. At this point at the cell edge, the UE can receive the signals of multiple antennas and might be interfered by the antenna, which it is not connected to. This fact needs to be regarded by the system design of the cellular system. It follows the fundamental limit for all communication systems and probably one of the most cited theorems, the Shannon-Hartley theorem [Sha48] in Equation (3.4). According to this theorem, the capacity C of a communication channel depends on the bandwidth B and the signal quality. Shannon originally regarded the Signal-to-Noise-Ratio as quality. However, in the radio channel with its broadcast characteristics, additional interference by other transmitters can be added to receive the Signal-to-Noise-and-Interference-Ratio $SNIR$.

$$C = B \; log_2(1 + SNIR) \tag{3.4}$$

The theorem shows the major advantage of a cellular system compared to a single transmitter that the capacity counts for every cell. The theorem further shows that the highest capacity is only possible at close distances, where the SNIR is high enough. A downsizing of the range and increase of the number of cells improves the overall capacity. However, it would reach a limit, as it also implies an increase of the interference between the cells. Another alternative would be the increase of the bandwidth. Yet, a higher bandwidth also means a higher noise level. Besides, national spectrum allocation plans typically limit the available frequency bands. The following concrete specifications for cellular networks will explain how engineers increase the capacity of the systems by mainly making more efficient usage of the available SNIR. In this way, they allow a higher spectral efficiency. Coming back to the problem of interference between cells, the simplest solution - as applied in GSM - is to use only a subset of the available frequency bands and change the frequencies with each cell [Gar07]. The same frequency can be reused again at a distant cell where the interference can be neglected. However, this approach leaves parts of the spectrum unused. The current systems of UMTS and LTE specify more sophisticated approaches [Sau13, Cox14].

The transmission delay is another important performance metric for the communication capabilities of cellular systems. The transmission delay is influenced by various factors, as the network topology and the protocols to handle the information transmissions as well as the mobility of the participants. The available capacity also has an effect on the latency as a high capacity means that more information can be transmitted within the same time.

Standardization

Today, the most common realizations of cellular networks are specified by the Third Generation Partnership Project (3GPP). Historically, the 3GPP was founded in 1998 to take over the evolution of GSM, the Global System for Mobile Communications. Before 3GPP, the European ETSI was responsible for the specification of GSM. Since then, ETSI is one important partner in the 3GPP-collaboration. Up to now, 3GPP designed two new systems with different architectures, namely UMTS (Universal Mobile Telecommunications System) and LTE (Long Term Evolution). As these systems are very comprehensive, 3GPP manages 17 specification series (21-37) with more than 2000 technical documents. This work is structured and published in releases [3GP17]. Table 3.2 outlines the release history with important features that are addressed later in this section. All administered families - GSM, UMTS and LTE - still receive updates with each release.

Due to historical reasons, there also exist different standard families for cellular systems which are not administered by the 3GPP. The CDMA2000 family from

Release	Date	Key Features
Pre Rel-99		GSM-Features
Rel-99	03/2000	Introduction of UMTS (WCDMA UTRAN)
Rel-4	03/2001	RoHC
Rel-5	06/2002	HSDPA (HARQ), IMS
Rel-6	03/2005	HSUPA, MBMS
Rel-7	03/2008	HSPA+, MBSFN, direct tunnel
Rel-8	03/2009	Introduction of LTE and SAE; continued HSPA+
Rel-9	03/2010	LTE eMBMS (MBSFN)
Rel-10	09/2011	LTE-Advanced (CoMP, HetNets - eICIC)
Rel-11	03/2013	HSPA+ multiflow
Rel-12	03/2015	LTE D2D in-coverage
Rel-13	03/2016	LTE D2D out-of-coverage
Rel-14	*06/2017*	*still open - LTE V2X*

Table 3.2: Key features of the 3GPP UMTS and LTE specification releases [3GP17]

the 3GPP2 (not to confuse with the 3GPP without 2) is popular in North America. Furthermore, the IEEE pursues an own line with the development of 802.16 WiMAX. Not directly involved in the standardization, the ITU develops recommendations about features for the systems. Their work is structured into generations. Hence, they have defined the well-known terms as 2G, 3G, 4G and so on. For comparison, UMTS and CDMA2000 are 3G systems. Even LTE in Rel-8 and Rel-9 is still a 3G system. Only LTE-Advanced and later meet the requirements for 4G. In the latest releases, the UMTS/HSPA family also heads towards the 4G specification. Marketing-speak sometimes refers to the terms 3.5G for HSDPA, 3.75G for HSUPA, or 3.8G for HSPA+ and so on, to distinguish enhancements towards earlier specifications. However, in the following, when the UMTS/HSPA and LTE systems are presented in closer detail, the generation terms are preferably avoided.

The prevalent user pattern for general purpose data traffic in cellular networks assumes as fast as possible transmissions of data bursts after asynchronous requests. Moreover, the communication typically bases on unicast between two participants. Consequently, the main improvements aim to optimize the systems for a higher capacity and also a shorter transmission delay [Sau13]. However, vehicular M2M communication use cases demand a different pattern, which can be regarded with certain functions. With the perspective towards the Internet of Things, particularly from Rel-9 on, interesting features for future machine type communication are introduced.

3.3.2 UMTS-HSPA Family

Initial System Design

At the time of GSM standardization, mobile phone networks only aimed to serve for telephony. Over time, data services like SMS (Short Message Service) and later GPRS (General Packet Radio Service) are included. The UMTS system still preserves the legacy of circuit switched telephony and SMS, but includes broadband packet switched data services from the beginning. The system design in Figure 3.6 shows the relation. UMTS consists of the typical three parts of a cellular system.

1. the UEs
2. the UTRAN (UMTS Terrestrial Radio Access Network)
3. the Core Network

The main innovation of UMTS (Rel-99) concerns air interface, accordingly the UEs and the RAN. The Wideband Code Division Multiple Access (WCDMA) air interface of the UMTS family separates the parallel transmissions of different users with different spreading or channelization codes [SL05]. Neighboring cells use a different set of channelization codes to cope with the interference problem from Figure 3.5. All cells together use the same carrier frequencies. With this technique, the allocated frequency band can be used more efficiently compared to GSM. As a result, UMTS in Rel-99 provides a capacity of 384 kBit/s. The core network is similar to and depending on the vendor even compatible with GSM/GPRS.

Starting from the left in Figure 3.6, multiple UEs communicate over the radio channel with the BS. This wireless interface is named Uu. The base stations are referred to as NodeBs. With the IuB interface, the NodeBs usually already have a wired connection to the Radio Network Controller (RNC). An example for the dimensions of the network allows that one RNC controls several hundred NodeBs and one NodeB can serve also several hundred UEs [Sau13]. According to this hierarchical structure, the RNC can schedule a soft handover between multiple NodeBs, when a UE moves to a cell edge. In a soft handover, multiple antennas are synchronized by the RNC and serve the same signal to the UE to achieve a better connection. For the case of voice calls or SMS (circuit switched domain), the RNC forwards the request to the MSC (Mobile services Switching Center). One MSC controls multiple RNCs in a region. It can directly switch to the dedicated RNC, if the other subscriber is in the same region; or to another dedicated MSC for the same network operator. Otherwise, it forwards the request

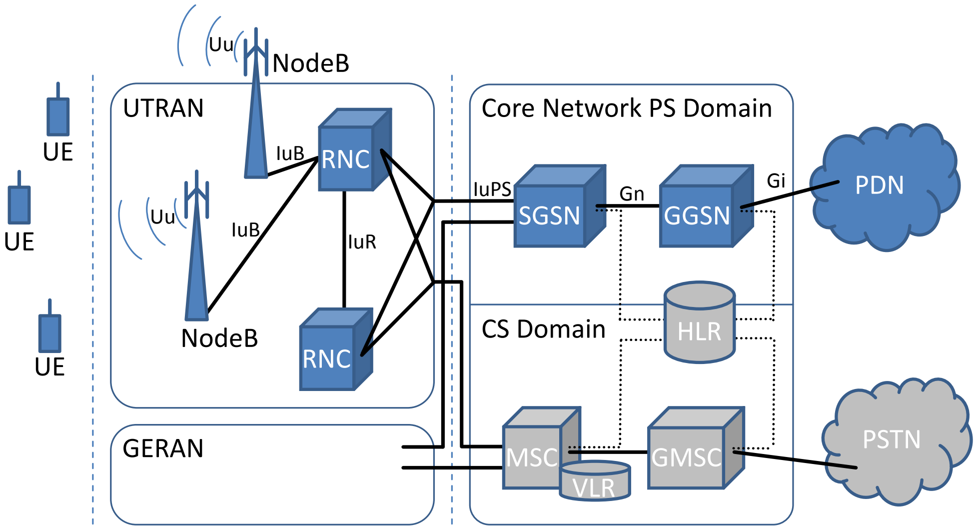


Figure 3.6: Reference architecture of the UMTS network (Rel-99)

via the MSC at the edge of the core network - the Gateway MSC (GMSC) - to the Public Switched Telephone Network (PSTN). All subscribers of one operator are stored in the Home Location Register (HLR). The knowledge about the subscriber position can be queried from the Visitor Location Register (VLR). The circuit switching functionality depends even on more components for authentication, billing etc., which also have been improved with later releases. A major innovation is the change to all-IP connections as the basis for the IP Multimedia Subsystem (IMS) in Rel-5. Due to clarity reasons, these components are not included in the figure. For vehicular use cases, the packet switching functionality is anyway the interesting one.

The procedure to exchange packets in UMTS shows the historical background of telephone engineering. A UE attaches to the network at power on. After this attach, the UE though can receive and send SMS or CS calls, but no packets. Still, it does not have an IP address. It needs to set up a UMTS bearer with the Packet Data Protocol (PDP) context as one important building block. A PDP context is a tunnel, extending from the RNC via the Serving GPRS Support Node (SGSN) through the PS domain of the core network to the Gateway GPRS Support Node (GGSN). In the establishment procedure, the SGSN and GGSN determine the subscriber settings as e.g. the maximum transfer rate from the HLR. The GGSN then assigns a dynamic IP-address and creates the tunnel. The SGSN maintains a signaling connection in the control-plane to the UE and changes the RNC address or even switches to another SGSN depending on the UEs mobility.

Figure 3.7 shows the protocol stack and the according interfaces for a typical user-plane packet transmission from an application on an Internet server - with

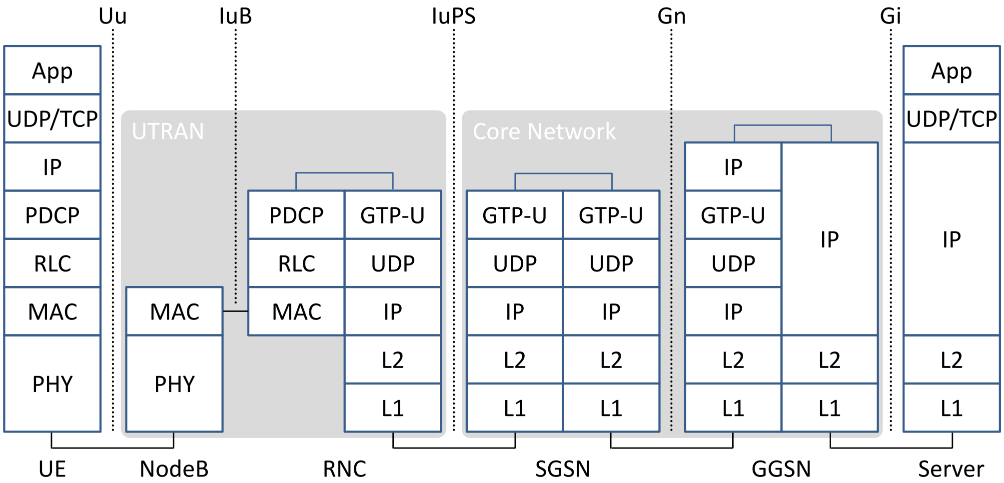


Figure 3.7: Protocol stack of UMTS (Rel-99) for packet data transmission

the Internet as a synonym for all connected Public Data Networks (PDN) - to the UE [Sau13]. The server on the right side of the figure has the typical TCP/IP protocol stack and always routes to the GGSN. The GGSN encapsulates the IP packet via the GPRS Tunneling Protocol (GTP) and forwards it to the SGSN. The SGSN tunnels this packet again to the RNC. The RNC decapsulates the GTP packet and uses the Packet Data Convergence Protocol (PDCP) for IP header compression and the Radio Link Control (RLC) to ensure the reliable packet transmission to the UE. RLC basically uses Automatic Repeat reQuest (ARQ) to acknowledge the packets. Finally, the MAC protocol schedules the resources on the radio channel jointly with the NodeB.

Communication Performance

The presented system design for UMTS induces an intrinsic latency for each transmission. For a similar constellation, a Round Trip Time (RTT) of 70-180 ms can be measured without the additional delay for the route through the Internet [SGV+09]. With 65-115 ms or 60-90 %, the RNC to UE connection contributes most to this delay. The latency results either from the network topology or from the technology of the signaling and protocols.

In some topologies where cabling is too expensive NodeBs connect via possibly multi-hop microwave direct antennas to each other and the network. This deployment is still common as can be seen at the typical round antennas at a NodeB site. Nevertheless, it is very delay expensive with the worst case RTT of 115 ms [SGV+09]. Traditional connections are specified via Asynchronous Transfer Mode (ATM) and fixed lines. Since ATM connections are limited to a capacity of 2 MBit/s, they possibly can become the bottleneck for more capable air interfaces.

The available capacity on a communication path is limited by the link with the lowest capacity. Today, ATM deployments decline in favor of all-IP networks with 100 MBit/s or GBit/s Ethernet or even fiber optic links. In Figure 3.7, the layers L2 and L1 for the Gi-, Gn- and Iu-interfaces though can be either ATM or Ethernet. Connection updates not only bring capacity improvements but also latency reduction. A reduction in the high range of single digit ms for each interface is reported, making all together more than 20 ms [SGV+09]. This arrangement accounts for a similar improvement as the co-location of certain network elements as 1) the RNC and the SGSN or 2) the SGSN and the GGSN, for faster routing.

Rel-7 publishes a further topology related update. The direct tunnel feature allows the SGSN to remove itself from the transmission chain in the user-plane while still being in line in the control-plane. It creates one tunnel from the GGSN directly to the RNC and merely forwards the packets like a usual IP router.

Many improvements are related to the technology of the UTRAN. Rel-4 introduces Robust Header Compression (RoHC) for the PDCP reduce the UDP and IP header size from 40/60 Byte to 1/3 Bytes for IPv4/v6. This feature addresses particularly the header to payload ratio for smaller packets that are sent frequently, as vehicular CAMs.

With HSDPA in Rel-5, more intelligence for medium access scheduling is shifted to the NodeB. The introduced Hybrid ARQ (HARQ) supports the RLC-based ARQ approach for more direct and very fast packet reliability. According to measurements [SGV+09], the introduction of HSDPA results in nearly the half of the latency in the UTRAN. In general, the HSPA line, starting with HSDPA, is one of the most important features ever specified for the UMTS family. It improved the system substantially, to the capability that is known today. WCDMA makes use of channelization codes with different lengths to control the bearer data rate for each user. The codes are derived from a code tree with orthogonal branches to receive a length of 2 up to 512 in downlink and up to 256 in uplink. Shorter codes allow a higher data rate, but invalidate the remaining longer codes of their branch. Rel-99 specifies the shortest code length of 8 for one user. This length is in line with the highest available user data rate of 384 kBit/s. The code length for a user is allocated in the bearer establishment phase. Theoretically, this static allocation scheme limits the number of users to eight to use the bearer with the highest data rate, practically to an even smaller number as the codes are shared with voice users. The dedicated channel lays waste in times when no packets are sent. HSDPA very much improves the allocation flexibility with the reduction of the Transmission Time Interval (TTI) and the introduction of shared channels in downlink [Sau13] The TTI is the interval of a data block, which is channel-encoded and interleaved for transmission. For this interval, the transmission parameters can be adjusted. A longer TTI improves the decoding possibilities of burst errors. A shorter TTI allows for faster link response. The minimal TTI is 10 ms since UMTS Rel-99 and 2 ms in HSDPA. Shared channels, as the name says, can be shared by multiple users, where each user gets a scheduled time slot for its transmission. Thus, HSDPA allows a way faster adaption to the dynamics of the radio channel. The time spans with high SNIR values can be used more efficiently to increase the transmission capacity according to Equation (3.4). For good SNIRs, HSDPA allows the utilization of higher order modulation. While UMTS specified QPSK to transmit 2 Bits with one symbol, HSDPA Rel-5 additionally allows 16-QAM (4 Bits/symbol) and 64-QAM (6 Bits/symbol) for good conditions. Due to the improvements, HSDPA supports already 14.4 MBit/s peak data rates in downlink for the best radio channel conditions. HSUPA in Rel-6 enables similar features for higher uplink rates.

Another step further is the introduction of Multiple Input Multiple Output (MIMO) antenna techniques. For example, 2x2 MIMO in Rel-7 uses two transmitter antennas and two receiver antennas to transmit two independent data streams simultaneously, using the same carriers. The data rate increases with the number of antennas, whereas 2x2 MIMO denotes a doubled rate.

Rel-8 specifies the carrier aggregation feature to utilize a higher bandwidth for increased capacity - Equation (3.4). The initial method, known as dual cell, bundles two adjacent 5 MHz UMTS standard carriers for a 10 MHz band. The HSPA+ multiflow feature in Rel-11 bases also on carrier aggregation. It revives a feature that is omitted with the introduction of HSDPA. Due to the shift of scheduling decisions to the NodeBs in HSPDA, soft handover between two cells is not possible anymore as the scheduler coordination over the RNC would take too much time. Multiflow allows the aggregation of multiple independent data streams on the same frequency carrier from two adjacent cells. Accordingly, it aims to improve the throughput at the edge of cells. Additionally, it can help to balance uneven loaded cells as unused resources from the adjacent sectors can be assigned to the UEs in the handover region.

The presented features aim for the typical pattern where independent users asynchronously request their own data transmissions. Furthermore, the Multicast Broadcast Multimedia Service (MBMS), which is already specified in Rel-6, delivers data transmissions more efficiently to multiple users. MBMS is primary intended to serve streaming and download use cases for UEs that signal interest in such services to the RNC. When the RNC receives a MBMS transmission, it employs the counting mechanism for the number of interested UEs to determine whether it is more economic to set up either multiple Point-To-Point (PTP) bearers or one Point-To-Multipoint (PTM) bearer. PTP bearers are transmitted alongside with other unicast traffic in the dedicated or shared channels, while PTM bearers use the separate Forward Access Channel (FACH). For few recipients, the setup of multiple PTP bearers is more efficient as it allows HARQ feedback and link adaption to the respective UE, though it means a replication of the packets. For more recipients, PTM bearers directly exploit the broadcast nature of the radio channel that all UEs in the cell overhear the signal anyway. Nonetheless, PTM bearers need to employ a lower and more robust modulation to increase the possibility of successful packet decoding at UEs with a low SNIR, which are e.g. at the cell edges. PTM bearers still include the chance of packet losses as it can merely use Forward Error Correction. PTM bearers get a channelization code that is shared for decoding by all addressed UEs. Rel-7 specifies an even more advanced MBMS version referred to as Multicast Broadcast Single Frequency Network (MBSFN). UMTS/HSPA already has a frequency reuse factor of one, which means that all NodeBs operate at the same frequencies. In the MBSFN mode, all participating NodeBs in the area use the same channelization codes and synchronize their packet scheduling for simultaneous transmission of the same PTM bearer. In this way, the UEs at the cell edges can benefit from multiple MBSFN signals to improve the packet delivery and avoid drops.

3.3.3 LTE (Advanced) Family

System Overview

Despite all improvements of the UMTS family with the introduction of the HSPA line, the change in the usage of mobile phone networks towards more data intensive applications raised the need for another major step to increase the system capacity and reduce the transmission delay. Therefore, the newly designed Evolved Packet System (EPS) envisions the evolution of the UTRAN and the core network [Cox14]. The activities for the Evolved UTRAN (eUTRAN) are named Long Term Evolution (LTE). The activities for the Evolved Packet Core (EPC) are named System Architecture Evolution (SAE). However, marketing-speak early promoted the enhancements under the LTE labeling, which now has become the synonym for the new overall system rather than EPS. Figure 3.8 displays the architecture of the new system.

The eUTRAN mainly improves two things. It introduces more spectrum efficient techniques to the air interface and it follows the HSPA approach to shift more intelligence (e.g. HARQ processing) to the evolved NodeB (eNodeB) to a major extent.

Topologically, the eNodeB now combines the tasks of the NodeB and the RNC, so that the RNC is removed completely from the system. The eNodeBs use a new X2 interface to connect to each other and the S1 interface to connect to the EPC. Due to this topology change, all handovers have to be performed as hard handovers as there is no central scheduling instance anymore. Nevertheless, LTE-Advanced in the later releases specifies more sophisticated mechanisms to facilitate good connections for users at the cell edge. This work item is referred to as Coordinated

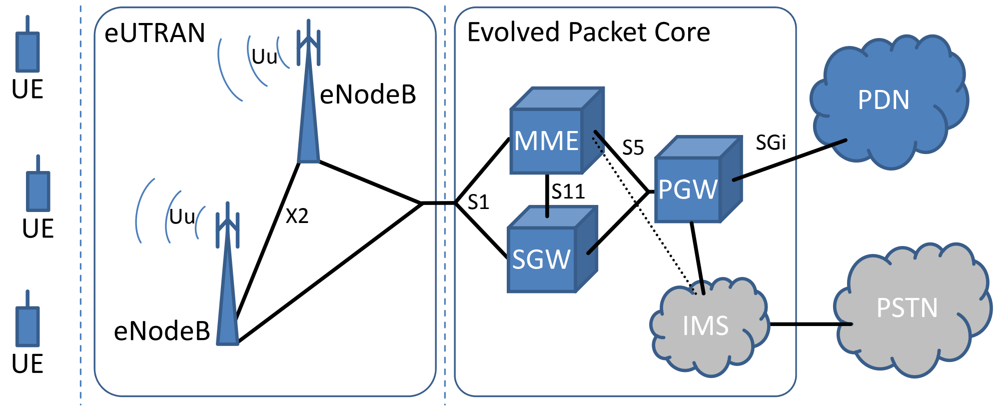


Figure 3.8: Reference architecture of the LTE network (Rel-8)

Multi-Point (CoMP). CoMP is described in more detail later in this section. Technologically, eNodeBs reduce the TTI to 1 ms for even faster channel adaption and scheduling. Furthermore, the simplification of protocols with a reduced number of states allows significantly decreased setup times before a transmission attempt. Also, shared channels, higher order modulation (64QAM) and MIMO antennas techniques are included from the beginning [HM04]. Additionally, LTE includes a more flexible bandwidth allocation, as regarded with HSPA carrier aggregation. While HSPA is able to aggregate bands of 5 MHz width, LTE - already in Rel-8 - designs the implementation in bandwidths of 1.4, 3, 5, 10, 15 or 20 MHz, to allow for different deployment scenarios. In later releases, LTE-Advanced also allows to scale the bandwidths up to 100 MHz.

The introduction of the modulation scheme OFDMA enables this straightforward scalability. OFDMA uses again a form of Frequency Division Multiple Access like GSM. Compared to GSMs FDMA, the carriers in OFDMA are arranged very close together and in a fashion to minimize the interference, hence being orthogonal to each other. The interference reduction becomes noticeable in areas with weaker signal strength. Also compared to the WCMDA code division approach in UMTS, OFDMA stands out with a higher robustness and spectral efficiency [SL05]. OFDMA in LTE resembles the OFDM in IEEE 802.11p, with the difference of the subcarrier spacing. With 15 kHz, LTE orders the subcarriers a much higher density than IEEE 802.11p, with 156.25 kHz. The general difference of OFDM and OFDMA lies in the channel access of multiple users. One OFDM frame carries data for only one user and multiple users are separated over the time. With OFDMA multiple different users can be scheduled at different subcarriers in the same time frame.

The EPC also comes up with massive improvements regarding the technology and the topology [Cox14]. Due to the all-IP design of the connections, the EPC is independent from the transport technology. As already explained for UMTS, the traditional ATM connections can become the bottleneck instead of the air interface. In later releases, this improvement is also introduced to the UMTS core network. Today, all connections are usually deployed with fast Ethernet or fiber optic transport. The major topological update of the EPC is the sole facilitation of packet switched services. The complete CS domain from the previous core network is omitted. The other evolution arises from the strong separation between the user-plane and the control-plane. Basically, the user-plane incorporates the protocols and functionalities to carry the actual network traffic, while the control-plane carries signaling traffic. In the UMTS direct tunnel feature, the SGSN follows a similar concept to avoid one IP tunnel for user traffic forwarding. In the EPC, the functionality of the SGSN splits into two logical entities, the Mobility Management Entity (MME) and the Serving Gateway (Serving-GW or simply SGW). Both components can be implemented on the same physical hardware. The MME is responsible for the control-plane. Consequently, it fulfills the tasks of UE location tracking and bearer establishment. As the EPC is optimized for sole packet switched services, the bearer establishment is much simplified compared to UMTS. When a UE attaches at the EPC, it directly gets an IP address assigned. The bearer establishment now mainly selects the right gateway to the Internet and instructs the SGW about this selection. The user-plane responsibility of the SGW means mainly forwarding of IP packets to this gateway. This gateway to the Internet is referred to as PDN Gateway (PDN-GW or simply PGW) and basically fulfills the same task as the GGSN in UMTS. Similar to the GGSN functionality, the PGW hides the UE mobility to the attached Internet routers and administers the IP address pool for address assignments to the registered UEs. As tunneling protocol, GTP is reused from the previous core network. In the EPC, the tunnel terminates directly at the eNodeB. The advantage of the new EPC architecture is a major reduction of the user-plane latency, which arrives in the single digit range [SGV+09].

Feature Improvements

Similar to UMTS, the specifications in later LTE releases concern further latency reductions and capacity enhancements. However, the high peak data rates can be realized only in good conditions and at locations close to the eNodeB [Cox14]. The signal quality at cell edges still exhibits impairments, due to the signal decrease at higher distances and the interference from adjacent cells. Thus, new features also concern more efficient mechanisms to maintain a good signal at cell edges. CoMP addresses any type of coordination between the radio communications in nearby cells. In the first instance, CoMP applies to the Downlink transmission. CoMP features intend different levels of coordination. In a simple scenario, a single three-antenna eNodeB can coordinate the three schedulers for each cell. A more sophisticated scenario coordinates multiple eNodeBs via the X2 interface. Such coordination allows the deployment of heterogeneous cellular networks (HetNets) with different cell sizes. In this way, HetNets use typical macro-NodeBs to have the general coverage and deploy pico-NodeBs with smaller coverage inside this network to offload data at certain hot spots. The handover mechanisms between this kind of cells is referred to as enhanced Inter-Cell Interference Coordination (eICIC). The standard specifies several varieties of CoMP. The main intention is an intelligent scheduling of user resource blocks to the appropriate frequencies for interference reduction. A variety named Joint Processing transmits the same data from different locations, similar to the soft handover in UMTS. Coordinated MIMO uses different data streams from different locations in a spatial multiplexing [HM04]. This feature is similar to HSPA+ multiflow.

The CoMP approaches basically address unicast communication. However, the intelligent coordination can also be applied for broadcast communication [Cox14]. In fact, eMBMS (enhanced MBMS) makes also use of coordinated and synchronized transmissions from multiple eNodeBs for the MBSFN variety. The general concept of eMBMS and MBSFN is similar to the one which is presented for the UMTS/HSPA family. Additionally, LTE introduces several improvements regarding the available bandwidths and the scheduling flexibility. LTE multiplexes both PTP and PTM bearers into the regular subframes of 1 ms in the downlink shared channel, whereas it allows assigning up to 6 subframes (60 % of the resources) for MBMS. Hence, even PTM bearers can benefit from HARQ feedback for a small the number of MBMS users in a cell. The feedback accordingly enables link adaption to the present radio conditions. For instance, LTE provides modulation schemes up to 64-QAM for good conditions. Regarding the integration of MBSFN, LTE specifies subframes with an extended cyclic prefix to cope with different delay spreads when the same signal is sent from multiple eNodeBs. Finally, an eNodeB can schedule its MBMS subframes in a way to be part of multiple MBSFN areas for an even more flexible integration of broadcasting services.

3.3.4 Suitability for V2X Communication

The main features for the standardized cellular architectures are designed to accommodate for a general purpose communication scheme. This scheme mainly consists of an unicast communication pattern on a managed channel. Before data transmission can be carried out, the channel needs to be established initially. Then, the central NodeB schedules the up- and downlink for all registered UEs in the cell. In this manner, the communication is contention-free. Accordingly, the development of cellular systems followed, for a long time, the three principles:

- Unicast communication pattern
- High data rates

- Low latency, but tolerable connection setup delays

When compared to the application categories from Section 2.1, comfort and infotainment use cases suite very well to this optimized user pattern for cellular systems. However, M2M use cases for improvement of safety and traffic efficiency exhibit different requirements.

The typical approach to concurrently inform all stations in a certain geographic area would be realized with the help of one or multiple central servers, which are located in the Internet. Several research projects as CoCar, simTD and CONVERGE implement a similar architecture. CoCar defines three components, namely the Reflector, the Geocast Manager, and the Aggregator [De09]. In simTD, the services for Reflection, Aggregation, Geocast Management, and Access are consolidated in the GeoServer [sim09a]. CONVERGE introduces the latest and most advanced concept. The architecture defines the Service Providers, connected to the Geo Messaging Proxy, which in turn connects to multiple Geo Messaging Servers [CON15]. This design allows the dissemination of information generated and managed by stationary central stations (i.e. the service providers) as well as the information exchange between the mobile stations (personal and vehicle stations).

For the exchange of typical CAMs and DENMs, the originating mobile station transmits the message with a specific geographical destination address to the Geo Messaging Server. Afterwards, the reflector component in the Geo Messaging Server delivers the message to all relevant stations in the designated area. Consequently, the transmission includes an uplink as well as a downlink part. The uplink part is always a point-to-point connection, while the downlink part can be realized as point-to-point or point-to-multipoint. The single sent message typically addresses to multiple receivers. It needs to be either replicated multiple times for multiple unicast connections or transmitted using the broadcast characteristics of the radio channel. Each of the directions can limit the communication performance under certain circumstances. The following sections discuss the different aspects with the focus on latency and capacity limitations. Prior to that, the next sections review the most important communication channels, which are in scope of this evaluation.

Considered Physical Channels

In UMTS/HSPA and LTE, the traffic for signaling as well as user data is exchanged over different channels. All channels exhibit a limited capacity and can get congested in certain cases.

PDSCH and PUSCH : The Physical Downlink Shared Channel (PDSCH) and, its counterpart, the Physical Uplink Shared Channel (PUSCH) carry the user data for the according direction of the transmission. Obviously, the congestion of these channels would limit the communication performance.

PDCCH : The Physical Downlink Control Channel is the most important control channel as it carries all management information from the NodeB to the UEs. The different types include mainly the downlink scheduling information, but also instructions for uplink power control and, especially important, the uplink grants. Besides, random access responses and paging information are transmitted over the PDCCH.

PUCCH : The Physical Uplink Control Channel has the purpose to carry uplink signaling information. To stay in the connected state, the UE periodically sends Channel Quality Indications (CQI) to the NodeB for channel estimation and link adaption. Additionally, the UE can acknowledge downlink transmission for the HARQ protocol. Moreover, the UE uses the PUCCH for SRs (Scheduling Requests) when it wants to send own user data in the PUSCH.

PRACH : For the establishment of the connection from the idle state, UMTS as well as LTE provide the Random Access Channels (RACH), each based on a time-slotted Physical RACH. More specifically, in UMTS the UE performs an open loop power control, which means that it repeatedly transmits a preamble with increasing transmission power until the acquisition is indicated by the BS. In the following 10 ms or 20 ms frame, the UE can transmit a small packet in the order of 20 to 80 Bytes, depending on the used spreading factor and frame length [BMA11]. UMTS allows up to 16 RACH to be configured by the network operators, but commonly only 1 RACH is used. The LTE procedure differs from the UMTS design, and already enables collision resolution of the preambles. This concept allows reducing the latency for the connection establishment.

Uplink Communication

For V2X use cases, the uplink communication performance can be limited for connection latency and capacity requirements in the following ways.

Regarding the issues of latency, it is argued that the connection establishment may take too long, especially for safety-critical messages. Hence, reusing the PRACH for faster information transmission is suggested several times [BMA11, MKH10]. Nevertheless, the restriction of the maximum packet length on the PRACH in UMTS may be an issue even for the small data amounts in V2X awareness messages. Longer packets than 80 bytes must be split up, involving the need for performing the RACH procedure for every part. LTE allows a better scalability for longer packets, as the concept turns away from the dedicated transmission resources [MKH10]. For the transmission of event based information in DENMs, the flexibility of fast random access may be preferable, at the price that only small amounts of data could be sent. In contrast, for the periodical transmission of awareness information in CAMs, the previous establishment of a connection and regular signaling on the PUCCH could be the better alternative.

As a result of the small amounts of data for V2X messages, the transmission in the PUSCH would be limited rather due to interference than capacity reasons [PRS11]. The interference increases with the number of vehicles to be served in one cell. Yet, the main bottleneck for the uplink transmission of many small packets is the PDCCH when it cannot sufficiently carry all uplink grants. With a message rate of 10 Hz, in LTE, *the PDCCH limitation can be observed at approximately 125 vehicles* in one cell [PRS11].

Downlink Communication

The downlink communication is mainly challenged by the number of targeted recipients. The traditional strategy of individual downlink unicast to every recipient would early lead to a highly loaded or even overloaded PDSCH when the number of vehicles increases [Vin12]. With a message rate of 10 Hz, in LTE, "*the Downlink is limiting for already 50 vehicles per cell*" [PRS11].

In contrast, the exploitation of broadcast features definitely increases the efficiency and reduces the load for such scenarios [ACC+13]. Still, in UMTS, MBMS offers low flexibility and response to the channel conditions. It comes at the price of the highest TTIs of 40 ms or 80 ms to provide a more robust signal against fading characteristics. For the originally intended purposes of media delivery sessions or big file downloads, which are characterized by a constant data stream over a longer time, such TTIs are perfectly acceptable. In contrast, for the relatively short safety-critical V2X message, an additional latency of 80 ms would be a considerable impairment and probably not tolerable. Moreover, the latency introduced by the TTI includes only the RAN part. The way through the core network and the processing in the geo server would contribute for an additional delay. On the other hand, LTE specifies massive improvements for the integration of broadcasting services. The multiplex of PTM bearers alongside within unicast bearers in the regular subframe with 1 ms TTIs provides the best possible flexibility for MBMS transmissions. Up to now, a very limited number of commercial networks are featured with MBMS. Media broadcasting over cellular networks is probably not the application of the greatest demand. Geographical messaging for V2X use cases is undoubtedly a reasonable use case to leverage the deployment.

Another important aspect for the communication performance originates from the implementation of the geo messaging server. Intelligent algorithms for aggregation and duplicate filtering before reflection can considerably reduce the data amount for the downlink transmission chain [PRS11, ACC+13].

Sidelink Communication

Obviously, direct communication between the mobile stations, also known as sidelink, allows the most considerable latency reduction, instead of going all the way in the uplink and downlink. With the emergence of the Internet of Things, machine type communication becomes more important and standardization activities of the 3GPP accelerate in this direction. Under the feature name LTE-direct, the latest Rel-12 includes aspects of Device-2-Device (D2D) communication [DRW+09]. The initial study is about D2D proximity services mainly focusing on public safety use cases [LAGR14]. One scenario envisions the mutual detection of a direct service. Additionally, the possibly offloading of data traffic between the devices to other wireless technologies as Bluetooth or even WLAN. However, service discovery for D2D communication in Rel-12 operates only in the band of the serving NodeBs. Moreover, it allows only for limited mobility. Rel-13 adds the option for serving UEs outside of the eNodeBs coverage area with a relay UE to forward the messages. This relay mode also enables service continuity for higher mobility scenarios. Finally, Rel-14 will directly address V2X scenarios with a feature set called LTE-V2X [LKK+16]. Rel-14 and LTE-V2X is still a work-in-progress feasibility study. However, it will need to answer very important questions such as the operation in in-coverage and out-of-coverage scenarios, different communication paths using either D2D sidelink or uplink and eNodeB broadcasting via eMBMS mechanisms, as well as the direct communication between different mobile operator networks.

Conclusion

All in all, for the end-to-end latency of V2X messages in LTE, round trip times that are considerably below 100 ms seem possible [WCML07, MKH10, PRS11]. Regarding capacity issues, LTE should be able to handle a sufficient number of vehicles. In contrast, UMTS would use a non-negligible amount of resources and would lead to quite high latencies of up to 350 ms on average [MKH10, BMA11]. In comparison, for 802.11p round trip times of 10 ms are commonly assumed.

A high traffic load in the cell for V2X communication would also have an effect on the other users with smartphones and surf sticks, which need to share the resources. Finally, the presented features of MBMS and D2D are of interest to improve the efficiency for V2X communication use cases. Nevertheless, for practical use, an important formal issue needs to be solved in advance. A solution needs to be found for the fact that different stations may be in contract with different network operators. Actually, every network operator has a separated infrastructure deployed, which is not compatible for scheduling of MBMS or D2D frames with other networks.

In contrast to ad hoc communication over WLANs, the operation of UMTS or LTE networks is not for free. Hence, suitable business models need to be developed to encourage the use of cellular networks for V2X applications [ACC+13]. Besides the already established comfort use cases, probably, traffic efficiency use cases with more relaxed timings are the first to be implemented with cellular communication before the safety-critical use cases.

3.4 Summary of Communication Technologies

With the unmanaged ad hoc communication according to IEEE 802.11p and the infrastructure based cellular systems of UMTS and LTE, this chapter discussed the two prevalent access technologies for V2X communication. Each technology has its own advantages and disadvantages. A principle of ad hoc communication is the exploitation of the broadcast characteristics of the radio channel. This goes well in line with the communication pattern of most V2X applications and results in typically low transmission delays. Unfavorably, the standard medium access coordination of IEEE 802.11p is not always reliable and can lead to recurring packet losses. Regular messages would accordingly need a higher sending period to compensate this drawback and achieve timely information refresh. Another disadvantage is the limited communication range. For the aspects of reliability and communication range, cellular systems exhibit significant advantages. Nonetheless, current systems of UMTS and also LTE introduce a notable transmission delay due to the possibly large wired backbone system. For these reasons, a feasible solution would implement time-critical applications with ad hoc access, while applications that require a higher dissemination area could be realized with cellular systems. The simulation study in Chapter 5 will evaluate if this approach to rely on heterogeneous networks proves beneficial. Before this investigation could be started, the simulation environment will be prepared, whereas the emphasis lies on the communication characteristics of the ad hoc and cellular technologies. The necessary implementations are discussed in the next Chapter 4.

Chapter 4

Simulation Environment

This chapter gives an overview about the work to set up the environment for the simulation of heterogeneous vehicular communication use cases. The work bases on the existing simulation framework VSimRTI, which is introduced in the first section. The second and the third part present a site-specific as well a statistic approach with the emphasis on more detailed radio propagation, which regard particularly for the ad hoc communication. Finally, a new dedicated simulator for the most relevant aspects of cellular communication is introduced. For all extensions on the environment, a dedicated simulation study presents the improvements, which can be achieved by modeling the additional aspects.

4.1 Existing Framework

Generally, the simulation of ITS incorporates different domains. In this thesis, the simulation study on ITS primarily regards for the investigation of V2X communication protocols and applications. For such purposes, the academic research community employs and develops discrete event simulators to cover the major aspects. Today, the most prominent representatives are ns-2 and its successor ns-3 [HLR^{+}08], OMNeT++ [VH08] and even JiST/SWANS [BHvR05]. These communication simulators are designed for different fields of communication research. For instance, they allow the investigation on the different layers of the communication stack. Moreover, they can be applied in different scenarios from small-scale to large-scale, where several hundreds or thousands of nodes are accounted.

However, meaningful investigations of ITS also need to incorporate realistic vehicular mobility patterns [HL10]. The state-of-the-art communication simulators as ns-3 or OMNeT++ already include basic mobility models with random waypoints or linear movements. One step further goes the offline generation of vehicular traces with dedicated traffic simulators before the actual simulation of the communication scenario. The academic SUMO [KEBB12] and the commercial VISSIM [FV01] are well-known instances for microscopic traffic simulators, where the movement of each vehicle is regarded individually. Still, this kind of sharing traffic patterns with the communication simulators is isolated and does not allow a further interaction between the communication and the traffic simulator [HL10]. More comprehensive simulation studies demand the interaction of the different simulators at runtime. For instance, the event when a vehicle receives information over V2X communication as a result of the communication simulation and dynamically adapts to this particular situation with slowing down or changing its route needs to be fed back into the traffic simulation. The following two interaction concepts enable such scenarios [HL10].

The Direct (Embedded) architecture intends to embed either a traffic simulator in a communication simulator or vice versa. This approach actually bases on a bi-directional coupling of the two simulators, where each simulator still preserves the own event processing mechanisms. One simulator acts as the master for the information exchange and time synchronization. It needs to ensure that all events in both simulators are processed in the correct order.

The Federated architecture bases on a central Runtime Infrastructure (RTI) that connects to each federated simulator via an ambassador interface. This approach is not limited to the coupling of two simulators, but allows the integration of multiple ones. The simulators only exchange information with the RTI. The RTI handles all further management tasks as for the information distribution towards the other simulators and the time synchronization of the simulation events.

Today, several multi-domain simulation environments exist for ITS evaluation. The following four tools are the most prominent ones.

- Veins [SYGD08]
- VISSIM-VCOM [KSEH+07]
- iTETRIS [HCK+11]
- VSimRTI [QSR08]

The Veins framework follows the direct interaction concept. It uses the communication simulator OMNeT++ as the master and synchronizes the traffic simulator SUMO at regular time steps. According to the Veins concept, the ITS application logic is implemented in OMNeT++ as a module on top of the communication stack. The VISSIM-VCOM also employs the embedded approach, whereas it interchanges the roles of the simulators. With the VCOM module, the traffic simulator VISSIM embeds a basic communication simulator and supports fundamental applications.

The iTETRIS project developed an architecture with a hybrid interaction concept. It supports the connection of the communication simulator ns-3, the traffic simulator SUMO, and multiple ITS applications to the iTETRIS Control System (iCS). The iCS handles the interaction between the simulators and the applications. Besides the simulation control, the iCS also implements application facilities according to the ETSI ITS standards.

VSimRTI is a development from previous work at the department [QSR08]. The architecture follows the federated interaction approach with VSimRTI as the runtime infrastructure. More specifically, it uses the most important concepts from the IEEE standard for Modeling and Simulation (M&S) High Level Architecture (HLA) [IEE10a]. According to this specification, all participating simulators are encapsulated in a federate and connect via an ambassador interface with the central management entity, which is the RTI. VSimRTI implements the following three core components from the complete set of interface categories in HLA.

The Federation management: VSimRTI controls the lifecycle of all connected federates in the simulation. It starts, joins and stops the individual simulators in the configured time frame.

The Interaction management: VSimRTI coordinates the message interactions between the federates. All federates only communicate with VSimRTI in the first instance. VSimRTI then distributes the messages to the federates, which have subscribed to the according information.

The Time management: VSimRTI regulates the synchronization between the independent processes of the simulation federates. In a joint procedure with the federates, VSimRTI grants the time advances for the local events that are either originated by a simulator itself or generated remotely by the other simulators in the federation.

Today, VSimRTI is vitally used for the evaluation of ITS applications to improve safety and efficiency in road traffic [SWR10] and enhanced with further features [Sch11]. During the time of this thesis, a comprehensive set of simulators and related components from specific domains is coupled to VSimRTI. Depending on the investigated scenario, the simulators can be exchanged flexibly. The following fields are covered with individual simulators:

- Traffic simulators: SUMO, VISSIM
- Ad hoc communication simulators: JiST/SWANS, ns-3, OMNeT++

- Cellular communication simulator: VSimRTI_Cell
- Application simulator: VSimRTI_App
- Environment event generators
- Electricity simulators: VSimRTI_BattSim, VSimRTI_Charge, OpenDSS
- Configuration and visualization tools

VSimRTI is the basis of the simulation investigations in this thesis. Particularly, OMNeT++ for ad hoc communication and VSimRTI_Cell for cellular communication simulation received substantial enhancements from the research and development that is connected with this thesis.

The following three sections accordingly refer to this work. Each section introduces a new feature set and illustrates the extensions on the basis of an exemplary simulation study.

4.2 Site-specific Propagation Models

Especially in urban environments, the presence of buildings leads to shadowing properties of the radio signal. In traditional propagation models, these properties are described with stochastic processes. However, for the evaluation of warning use cases where every individual message is important, stochastic models may be too simplistic. Shadowing due to buildings leads to a low reception quality in particular constellations of transmitter, receiver and buildings (see the hidden terminal scenario in Figure 3.4b).

This section introduces site-specific propagation models to account especially for such scenarios [PSR14a]. The models base on efficient ray tracing techniques to identify the locations of buildings in the surrounding of the transmitter. They consider the effects of shadowing, penetration and diffraction to achieve a more accurate result. The following simulation analysis for the use case of the warning of Approaching Emergency Vehicles (AEV) compares the developed propagation models with a commonly used stochastic model. The AEV warning stands representative for the class of safety applications where moving vehicles permanently communicate their current state. According to the ETSI road safety model, the AEV warning addresses the information zone, which means a high range communication range with medium critical timing requirements. The simulation will show that the stochastic model leads to overoptimistic propagation conditions in the investigated scenario. In contrast, a more credible result for the performance of the AEV warning can be achieved when the site-specific models are applied. Before this, the next part briefly resumes the prevalent approaches for propagation modeling.

4.2.1 Modeling Approaches

As stated in the previous Chapter 3.1, the possibility for successful reception of the radio signal depends on the signal power and the spread of the individual multipath components towards frequency and time. Hence, propagation models commonly regard at least for the path loss of the signal. More detailed models also consider the fading characteristics. The prevalent approaches for modeling can be divided into the following categories [Rap02, MTKM09].

- Analytical models
- Stochastic models
- Empirical or Statistical models
- Ray Optical models

Free Space Propagation Model

The Free Space Propagation Model is the most simplified analytical model. It bases on the assumption of a clear and unobstructed LOS path between the transmitter and the receiver. With the free space path loss $L_p = L_{fs}$ from Equation (3.3) this model calculates the received power P_r as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L_o} \tag{4.1}$$

where P_t is the transmitted power. G_t and G_r are the antenna gains of transmitter and receiver respectively. The free space path loss depends on the wavelength λ of propagating wave and the distance d between transmitting and receiving node. Other losses which may be not directly related to propagation are expressed with L_o. This equation is commonly known for a long time as the Friis equation [Fri46].

For link budget calculation, Equation (4.1) is usually written in the decibel notation. One gets the following form.

$$P_r[dB] = P_t[dB] + G_t[dB] + G_r[dB] - L_o[dB] - L_{fs}[dB] \tag{4.2}$$

The link budget notation in Equation (4.2) is also typical for empirical propagation models. Moreover, it will be used for the presentation of the developed site-specific models later in this section.

Two Ray Ground Reflection Model

The slightly more detailed analytical Two Ray Ground Reflection Model considers the superposition of the direct path from the Free Space Model and a second path, which is reflected from the ground. The important factor for the reception quality is the phase shift as a result of the length difference between the both paths. The following Equation (4.3) represents the general notation on the left side and the notation after the application of a Taylor series approximation on the right side.

$$P_r = \frac{P_t G_t G_r}{L_o L_p} \sin^2\left(\frac{2\pi h_t h_r}{\lambda d}\right)^2 \rightarrow P_r = P_t G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2 \tag{4.3}$$

The Two Ray Ground Reflection Model additionally depends on the antenna heights h_t and h_r of the transmitter and the receiver towards the ground.

Rayleigh and Rice Fading Models

The Rayleigh and the Rice Fading Models are the best known models to account for fast fading characteristics. These stochastic models understand fading as a random process and apply the Rayleigh or Rice probability distribution.

Rayleigh Fading occurs when the multipath components at the receiver exhibit nearly the same amplitude, but different delays. In other words, Rayleigh Fading regards for conditions without a strong LOS path. The characterizing probability density function f for the according Rayleigh distribution depends on the distance d between the transmitter and the receiver and the local power σ at the receiver.

$$f(d) = \frac{d}{\sigma^2} e^{-\frac{d^2}{2\sigma^2}} \tag{4.4}$$

Rice Fading is basically a generalization of Rayleigh Fading and considers also LOS conditions. More specifically, it accounts for one strong direct signal and multiple NLOS signals with weaker contribution. This assumption goes well along with the general understanding that (1) partial signal energy from indirect paths is absorbed through reflection and (2) a longer reflected path implies a higher attenuation. The Ricean K-factor defines the relation between the dominant LOS path and the additional NLOS paths. The distribution is given as follows.

$$f(d) = \frac{d}{\sigma^2} e^{-\left(\frac{d^2+K^2}{2\sigma^2}\right)} I_0\left(\frac{Kd}{\sigma^2}\right) \tag{4.5}$$

The special case $K = 0$ implies that no LOS path exists. With the Bessel function $I_0(0) = 1$, Equation (4.5) transforms into Equation (4.4) in this case. Hence, Rice Fading transforms into Rayleigh Fading, which is usually applied for NLOS conditions.

Log-Normal Shadowing Model

The Log-Normal Shadowing Model in Equation (4.6) is a stochastic model, particularly suited for slow fading or shadowing characteristics.

$$L_p(d)[dB] = L_p(d_0) + 10nlog\left(\frac{d}{d_0}\right) + X_\sigma \tag{4.6}$$

This model bases on a calculated or measured reference path loss at the distance d_0 and a more generalized log-distance path loss with the exponent n (e.g. with $n = 2$ in free space). Moreover, it introduces a Gaussian distributed random variable X_σ with the standard deviation of σ to account for the severity of shadowing conditions.

Empirical Models

Empirical or statistical models are derived from real world measurements of exemplary communication processes with equipment referred to as Channel Sounders. As an advantage, the measurement approach accounts for all characteristics of the radio channel. Even aspects that are not entirely understood or analytically modeled can be considered. Thus, empirical models are able to outperform the prior models, which always abstracted from particular details. However, empirical models need to respect that the channel characteristics depend highly on properties as the antenna design, the transmission frequency, the investigated terrain profiles and others. Due to this, the particular models usually exhibit a limited range of application for specific scenarios.

The Okumura-Hata model is a widely known empirical model. It bases on a measurement campaign, performed by Okumura et al. in the urban area of Tokyo [OOKF68]. From these measurement recordings, Hata derived three link budget equations for the median path loss in the environments of typical urban, suburban and open areas [Hat80]. The European Cooperation in Science and Technology (COST), which has a strong background in propagation modeling, developed and published a variety of suitable models. The COST Hata model as an extension to the Okumura-Hata model is probably one of the most cited models from the COST action 231 [DCe96]. Furthermore, the ITU-R maintains a series of recommendations for propagation modeling, which also includes empirical models [ITU13].

The advanced propagation models, introduced to the simulation framework in Section 4.3, are statistical models as well.

Ray Optical Models

Ray Tracing has its origin in the area of computer graphics for image or scene rendering. Moreover, the approach can be applied for the simulation of electromagnetic field propagation. The propagation itself is described by multiple rays or ray tubes, which are launched from the transmitter node in a dedicated angle, with an initial strength of the electromagnetic field. This method even allows modeling particular antenna characteristics. For instance, an omnidirectional antenna can launch 36 rays in the interval of 10 degrees with equal field strength. A higher resolution can be achieved with more rays, at the price of higher computation costs. In a fully fletched ray tracing model, each ray is traced through a binary tree during the propagation [LB98]. Depending on the implementation, geometrical methods or even approximations for Maxwell's equations are used to calculate the phenomena of the radio propagation. Reflection is represented as a node in this tree, with a reflected and penetrating part. The direction of the emergent ray is calculated with Snell's law. Diffraction leads to the generation of a set of new ray tubes, according to Huygens' law. In particular, diffraction leads to a recursive process with the result of a high computational load in according environments. The ray tracing procedure finishes either when the ray arrives at a receiver; a ray leaves the simulation area or when the electromagnetic field strength falls below a certain threshold (e.g. the noise floor).

Ray tracing requires a detailed description of the scenario with the according scatterers to show its strength. Otherwise, it could be simply displaced with more simplified models, which are computationally less demanding.

The developed propagation models in this section find a solution to the challenges of ray tracing in larger scale scenarios. With an efficient environment representation and a reduced number of launched rays, they exhibit the accuracy advantages of ray tracing at low computational complexity.

4.2.2 Developed Models

As already mentioned, one key prerequisite for ray tracing is the detailed description of the scatterers in the scenario. Prior to the presentation of the propagation models themselves, a brief introduction should be given particularly about the representation of buildings in the simulation environment.

Building Representation

The source for all map data in the simulation is OpenStreetMap (OSM) [HW08, Ope14]. The map data includes certainly the street network for the vehicle movement simulation as well as buildings, which are employed as the scatterers for the radio propagation simulation. OSM basically implements a two-tier concept to represent the location and the shape of any map object.

1. It locates *Nodes* on the earth's surface with a defined position using geographic latitude and longitude coordinates.

2. It defines *Ways* by referencing an ordered list of nodes. Ways can define polylines to represent linear objects as roads, and polygons to represent areas.

The third basic elements in OSM - Relations - specify the correlation between multiple basic elements and can be used for multiple purposes, as the definition of turn-restrictions or bus routes. However, for the building definition, only Nodes and Ways are needed. In particular, for buildings the first and the last entry of the ordered list of nodes refer to the same node to complete the loop for the polygon that represents the area of the building. The accordingly defined ways correspond to the walls of the building, while the used nodes are basically the corners. This representation is directly adopted for the site-specific simulation models. Furthermore, the building information is augmented with a so-called abstracted area. The abstracted area can be seen as a rectangle with the maximum expansion of the building. When the propagation models need to calculate the signal reception, they initially fetch all buildings in the vicinity of the communicating nodes. More specifically, they query all buildings where the abstracted area is within the area between the transmitter and the receiver.

The existing data are structured into a database with three tables.

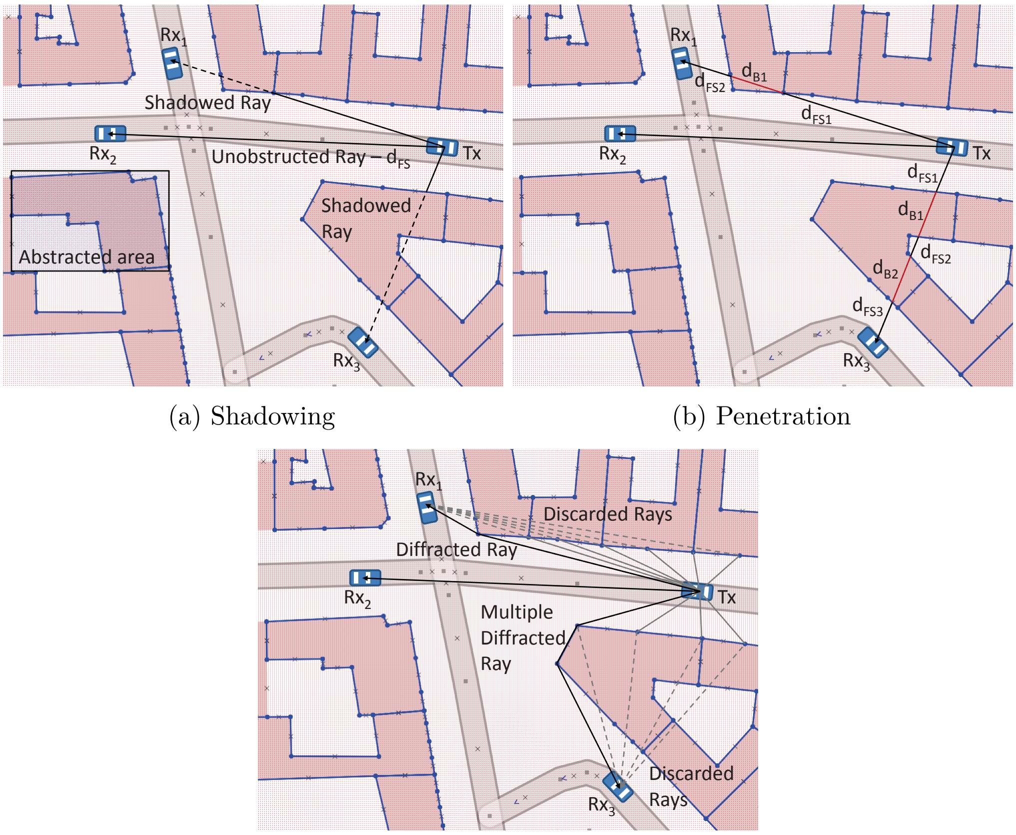
- Corners: contains the 2-dimensional position information for each corner
- Walls: contains the reference corners as well as the corresponding building
- Buildings: contains the abstracted area information of the building

The vector based representation of the building and map geometries allow a significant reduction of the number of rays for the models. Hence, the impact on the computing effort is still within reasonable limits. The Shadowing and the Penetration Model will actually need only one ray. The Diffraction Model will need to launch multiple rays to determine the according diffraction corners of the buildings.

Shadowing Model

The Shadowing Model is the simplest one of the presented site-specific models. After the first step of fetching all buildings according to their abstracted area, it draws one single ray between the transmitter and possible the receiver. This technique is also referred to as Primary Ray Tracing [Rap02]. In geometrical sense, it calculates a line segment $[TxRx_n]$ between the current positions of the transmitter and the receiver.

The actual determination of the reception consists of a nested loop over all walls of all fetched buildings in the vicinity. When an intersection of the line segment $[TxRx_n]$ and an according wall is calculated, the signal is considered as shadowed. For this reason, the Shadowing model returns the most restrictive reception conditions. The advantage of the Shadowing Model lies in its computing efficiency. When the first intersecting wall is found, the nested loop can break and



(a) Shadowing

(b) Penetration

(c) Diffraction

Figure 4.1: Ray tracing constellation of the three Propagation Models, underlying visualization based on map from OpenStreetMap [Ope14]

skip further calculations. In the case when the ray is unobstructed, the receive power is calculated by the log-distance path loss.

Figure 4.1a shows an example where the Rx_1 and Rx_3 will not receive the signal. For Rx_2, in the LOS condition, the reception will depend on the path loss over the free space distance d_{FS}. Moreover, Figure 4.1a includes the abstracted area, which is used for fast queries of the buildings in the surrounding of the transmitter. The Shadowing Model is comparable to the propagation model presented by [MFC+10].

Penetration Model

The Penetration Model uses the same technique as the Shadowing Model with the launch of single rays between Tx and all Rx and the calculation of wall intersections. However, it does not skip the evaluation upon the detection of the first intersection but calculates all intersections. In this manner, the model can count all penetrated walls w and determine the individual distances through the buildings d_b. Accordingly, d_{fs} is the distance the signal travels through the free space (see Figure 4.1b). The Penetration Model bases on the path loss equation for link budget calculation. The formula is extended to sum up all partial losses along the primary ray and turns out like Equation (4.7).

$$L_p(d)[dB] = L_p(d_0) + 10nlog\left(\frac{d_{fs}}{d_0}\right) + \sum(\alpha d_b + \beta w) \tag{4.7}$$

Compared to the restrictive Shadowing Model, the Penetration Model includes more physical details, yet it is computationally still inexpensive. In fact, this model yields very accurate results, when the attenuation factors α (signal loss per meter of the building interior) and β (signal loss at one building wall) are selected appropriately [Rap02]. It already exists a wide range of attenuation factors, measured at different frequencies [Rap02]. Even for the preferable range at 5.85 GHz, detailed measurement campaigns for further collections are realized [DRX98]. The Penetration Model shows similarities to the model presented by [SEGD11], with a slightly different usage of the attenuation factors.

Diffraction Model

The Diffraction Model is already more complex. The Fresnel geometry of diffraction requires multiple rays to determine the diffraction corner when the direct path between transmitter and receiver is obstructed (see Figure 4.1c). The Huygens principle states that a new wave source originates at the point of diffraction. According to this, the Diffraction Model assumes a tuple of an initial ray from the Tx to the building corner and a second ray from the corner to the Rx for all potential corners in the setting. Most of the ray tuples can be discarded at this step as they would end in an obstruction again. The remaining tuples are used to calculate the Fresnel-Kirchhoff diffraction parameter v [Rap02]. The v-value is then applied to the Knife-Edge Diffraction Model provided by Lee to receive the diffraction loss L_d for the individual corner [Lee97]. Finally, the path with the smallest diffraction losses on the way is selected to be applied in the modified path loss Equation (4.8).

$$L_d(d)[dB] = L_p(d_0) + 10nlog\left(\frac{d_{fs}}{d_0}\right) + \sum L_d(v) \tag{4.8}$$

4.2.3 Simulation Study

In the following section, the three developed propagation models are applied for the investigation of the V2X communication use case for an Approaching Emergency Warning (AEV). The focus of this investigation lies on the comparison of the developed site-specific propagation models with a stochastic modeling approach, represented by the Log-Normal Shadowing Model. This study uses mainly the following three simulators.

- The Communication Simulator (OMNeT++ with INETMANET), including all needed propagation models.
- The Application Simulator (VSimRTI_App) for the applications on the road user vehicles as well as the emergency vehicle (EV). The applications are explained in the first part of this section.
- The Traffic Simulator (SUMO) to create a realistic traffic situation. The scenarios are presented in the second part of this section.

Applications

The AEV warning use case comprises two different groups of actors, namely the EV itself as a sender and the other vehicles to be informed about the EV as receivers [BSKW09]. When an emergency vehicle needs to inform others about its right-of-way, the sequence of action includes four steps. The EV (1) prepares the relevant information and (2) disseminates the warning messages. Upon reception, the other vehicles (3) determine their relation to the EV and (4) possibly inform or warn the driver. On the side of the road user vehicles, a fifth step would include the message forwarding to further vehicles. This step is not used in the current study as the evaluation focuses the influences of the propagation models on the effectiveness of the warning application. The investigated applications implement the following algorithms:

The Emergency Vehicle (1) prepares a cooperative awareness message (CAM) and includes the information of the own position, the current speed and the heading in the warning message. Optionally, it can include its driving route. However, with the additional route information, the message length would increase accordingly and thus the probability of a message collision. For this reason, as well as privacy issues, it is proposed to include only a partial route [BSKW09]. Finally, the need for the right-of-way is included to distinguish the warning message from regular CAMs. (2) The messages are sent periodically via the ETSI ITS CAM sending mechanism with regularly updated values of the included information [ETS14a].

The Road User Vehicles (3) first calculate the own area in relation to the EV. More specifically, the vehicles compare the trajectories of the received information from the EV and the own current state to calculate a time-to-approach (TTA). As the trajectory comparison can contain deviations, the algorithm includes a tolerance margin, particularly for the speed and heading component. This means, that a set of slightly different trajectories is compared to calculate a safe TTA. Obviously, with smaller distances and a higher frequency of message receptions from the EV, the differences between the alternative trajectories also decrease and the TTA calculation gets very precise. The determined information are adopted from the AEV warning used in the German field test simTD [sim09a], where the Relevance Area and the Operational Area were defined.

- *The Relevance Area* involves all vehicles within a certain distance to the EV. Vehicles driving in the opposite direction of the EV, having a divergent trajectory or a convergent trajectory, but arriving with a time delay at the same intersection are in this area.
- *The Operational Area* involves the vehicles, which are directly affected to initiate a particular action to prevent a dangerous situation. Vehicles with a convergent trajectory are in this area.

The last step of the road user vehicles (4) of the information presentation is out of scope of this investigation. The issue would depend strongly on the OEMs or aftermarket suppliers and their customers. For instance, the presentation could display a secondary information message for vehicles in the relevance area and a remarkable warning message for vehicles in the operational area.

Traffic Scenarios

Figure 4.2 depicts the two analyzed scenarios, in an inner-city setting (on the left side) as well as in a sub-urban environment (on the right side). In this picture, the EV is the red-colored vehicle with blue lighting. The road user vehicles are depicted in blue color. The number of road user vehicles is 20. The vehicle routes (in red and blue) cross or join at the upcoming intersection. Both scenarios exhibit similar characteristics regarding the course of the streets. The used streets converge in an acute angle. Connecting streets allow intermediate line-of-sight conditions. The significant difference in both scenarios concerns the kind of buildings. In the inner-city setting, most buildings are erected as perimeter blocks in Wilhelminian Style with mainly closed street intersections. In the suburban environment, detached houses prevail. The main intention for the scenario-selection is to identify, if more abstract propagation models lead to wrong, probably overoptimistic assumptions for the information exchange and thus for the functioning of the application.

Results

The evaluation analyzes the percentage of vehicles which successfully recorded the event of being in one of the previously introduced areas. A post processing tool that has the knowledge of all vehicle positions of all simulations times determines the vehicles' area with the same algorithm as the introduced applications. It compares whether the vehicles have recorded the successful AEV warning or not.

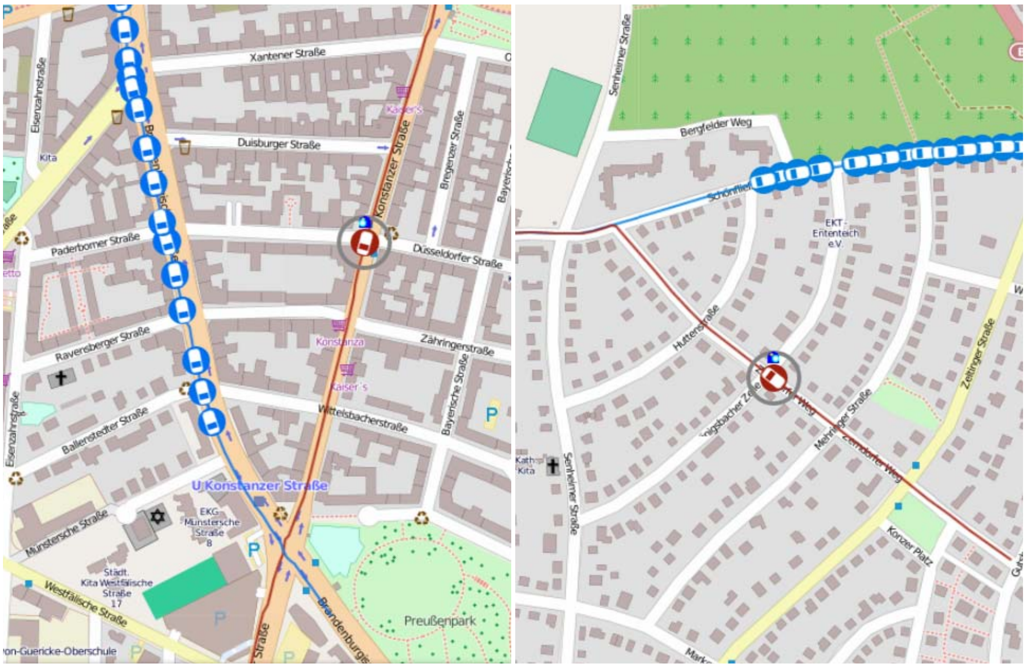


Figure 4.2: Simulation scenarios for the evaluation of an AEV warning application (left: inner-city, right: suburban), visualization based on map from OSM [Ope14]

Component	Parameter(s)
EV-CAMs	$frequency = 1\ Hz$
PHY Layer	$txPower = 50\ mW$, $rxSensitivity = -81\ dBm$
Pathloss	$n = 2\ dB$
Log-n Shadowing	$n = 2\ dB$, $\sigma = 7\ dB$
Penetration Model	$\alpha = 2\ dB$, $\beta = 5\ dB$

Table 4.1: Simulation parameters for the study on an AEV use case to compare the Log-n Shadowing - and the site-specific propagation models

In particular, the evaluation assumes the Relevance Area within the distance of 300 m to the EV and the Operational Area with the $TTA <= 10\ s$, similar to [BSKW09]. The communication parametrization is collected in Table 4.1.

The communication stack bases on the IEEE 802.11p compliant implementation of the OMNeT++/INETMANET simulation framework. All CAMs are sent with single-hop broadcast without prioritization.

Figure 4.3 and 4.4 display the simulation results for the four applied propagation models. The figures include a variation of the vehicles to be silent and just listen to warning messages (w/o comm). However, these vehicles would usually also communicate periodically via own CAMs to enable other use cases apparent from AEV (with comm).

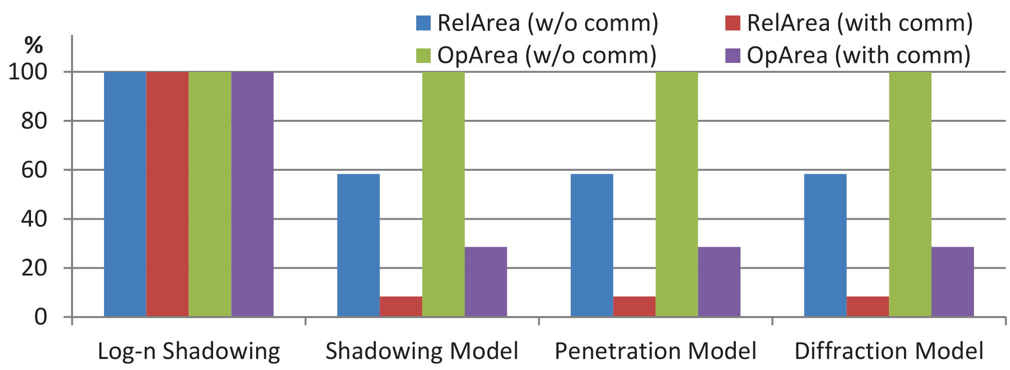


Figure 4.3: Percentage of successfully informed vehicles in the inner-city setting

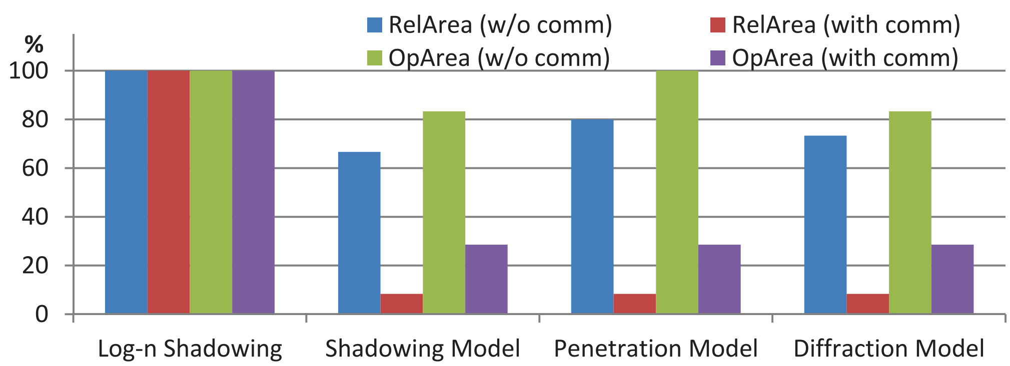


Figure 4.4: Percentage of vehicles with successful message reception in the suburban environment

The Log-Normal Shadowing leads in any case to the information of all vehicles, already in the Relevance Area and also in the more important Operational Area. Even though not every message is received, it meets the requirement for at least one message to get informed. The figures turn out different and less optimistic for the site-specific models. While the applications work still sufficient without communication of the other vehicles, it degrades very strong in the case with communication. Obviously, the probability is very high that individual vehicles are shadowed from the EV message transmission and send their own CAMs to cause a collision at the potential non-shadowed receivers. The well-known hidden terminal problem arises. Comparing the site-specific models among each other, the Shadowing Model is the most restrictive. The Diffraction Model allows just slightly more successful transmissions. Due to the high operating frequency of 5.9 GHz, Lee's diffraction loss gets very high. In the figures, no difference can be identified between the Shadowing and the Diffraction Model. Hence, the question arises if the computationally more expensive multiple ray launch of the Diffraction Model is worth to be used in such scenarios, which are not sensitive to these details. In the inner-city setting, the Penetration Model leads to similar results as the Diffraction Model with regard to the individual message transmission. The penetration loss through the buildings is many times too high, due to the perimeter block development. Consequently, no difference can be identified for the metric of informed or warned vehicles. In contrast, in the suburban-scenario the probability of message reception is high enough to be visible with the presented metric. It is still far less optimistic compared to the Log-Normal Shadowing.

4.2.4 Summary

This section discussed how the site-specific modeling of radio propagation effects of shadowing, penetration and diffraction influences the functioning of the approaching emergency vehicle warning. The models base on a ray tracing method with a reduced number of rays for faster computational performance. The locations of scatterers, especially buildings, in the environment can be imported from OSM data and used for larger scale scenarios. Compared to the stochastic consideration of buildings in the Log-Normal Shadowing Model, the results are less optimistic with site-specific models and reveal certain shortcomings of the application itself. For instance, the presented application is prone to the hidden terminal problem. It could be improved with a component that forwards the warning information to other shadowed vehicles. Although the simulation study concentrated on the specific application of the AEV warning, the conclusion should be that more realistic propagation models are important for investigations on V2X applications in general. Especially in urban environments, shadowing is a significant aspect that influences the communication performance of V2X applications.

4.3 Advanced Statistical Communication Models

The previous section about site-specific propagation models confirmed that the detailed consideration of the communication properties on the lower layers is crucial to achieve a correct result for applications. Nonetheless, the presented models still include several abstractions. For instance, they do not consider the vehicle speed dependency and thus the Doppler Effect with connected fading characteristics. As mentioned, statistical models can account also for such aspects. In recent times, more appropriate measurement based vehicular channel models were proposed [MTKM09]. The integration of these advanced statistical models into the vehicular simulation environment is a desirable objective. For instance, an initiative improved the ns-3 Physical Layer with a detailed signal-processing chain including OFDM modulation and convolutional coding [MPHS11]. Furthermore, it includes more sophisticated models for the radio channel effects.

The following section presents another way to include detailed models for both the radio propagation and the signal processing on the Physical Layer in the simulation of V2X communication. According to this approach, a new component for MATLAB based communication models is integrated in VSimRTI [PMOR12]. The component is called the Car2X Channel Model Simulation (CCMSim). According to the proposed architecture, the higher layers in the communication stack up to the MAC Layer are still simulated with a network simulator. In the specific case, this is OMNeT++ with the INETMANET model library. So, the major challenge of this approach is to enhance CCMSim for discrete event simulation and develop the connection between the OMNeT++ (INETMANET) MAC Layer and CCMSim lower layers.

4.3.1 Qualification

CCMSim is a MATLAB based simulation tool that includes an IEEE 802.11p Physical Layer implementation and a statistical vehicular channel model. This empirical channel model is based on data from extensive measurement campaigns in different scenarios, using the HHI Channel Sounder [PWK+08]. Owing a bandwidth of 1 GHz, this measurement equipment allows the resolution of paths within 1 ns (30 cm). From this highly detailed measurement data, all relevant path parameters were identified and modeled statistically, including the channel gain, the number of paths, the delay of paths, the path power and the small-scale fading of paths. Input parameters of a simulation include the environment (highway or urban), the movement constellation (e.g. oncoming or convoy traffic), the speed and the distance between vehicles.

A major concern of vehicular communication is the highly time-variant nature of the vehicular radio channel. One aspect of the time-variance is the small-scale fading that each path undergoes. A physically motivated model approach was proposed in [MPKK10]. The time-variance of the channel can cause for instance the channel estimation at the beginning of a received packet to become invalid over the duration of a packet reception. In order to account for this effect, CCMSim joints the packet frame and the time-variant channel realization by using an integral transform operator.

4.3.2 Implementation

The introduction of the MATLAB based CCMSim is a special case for VSimRTI simulations, as the properties of the communication domain are simulated with two Federates, OMNeT++ for the higher layers in the communication stack and CCMSim for the Physical Layer and the radio channel. The partition is illustrated in Figure 4.5. Among the major challenges of this architecture are the integration of the CCMSim according to the paradigm of discrete-event simulation and the logical connection between the OMNeT++ MAC model as the representative of the higher layers and the CCMSim PHY Layer. Figure 4.6 highlights the

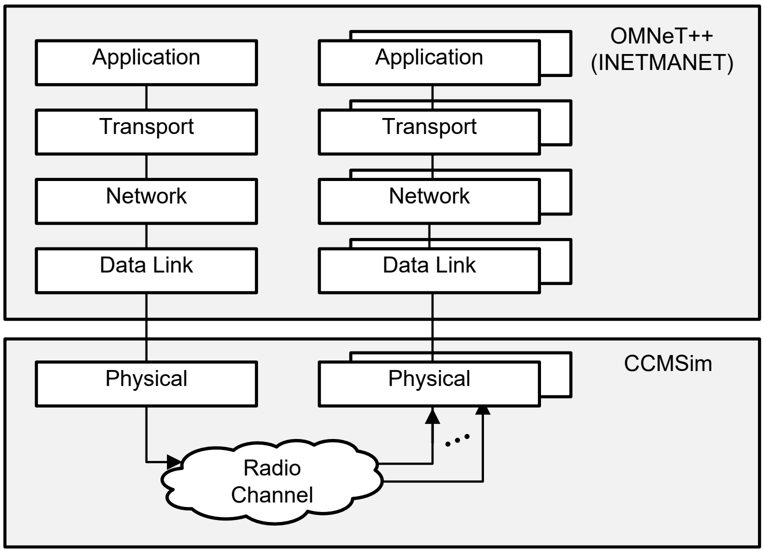


Figure 4.5: Partition of the communication stack between OMNeT++ and CCMSim

main components of the designed architecture for the coupling of OMNeT++ and CCMSim.

As an advantage of the VSimRTI concept of loose coupling, the other components in the federation as the traffic simulator or the application simulator can be left unmodified. Due to this, these simulators are omitted in the Figure 4.6.

During simulation runtime, two main sequences are particularly important. These are on the one hand the periodic updates of vehicle positions and the following calculation of the radio channel matrices. The sequence on the other hand is the event driven message transmission procedure over the two simulators OMNeT++ and CCMSim. These sequences are explained in more detail in the following.

Periodic Vehicle Movements

The radio channel is influenced by the values of node positions, speeds and headings. These parameters are periodically simulated by the traffic simulator in one simulation step and need to be updated in the CCMSim. Hence, CCMSim uses the same subscription method for vehicle movement information as the application simulator VSimRTI_App and communication simulator OMNeT++.

When the movement information is received at the CCMSim Federate, it is stored in a first matrix NodeRepository. In this step, the relative speeds and directions between the nodes can already be determined. They are important to distinguish between traffic situations where vehicles move towards to or away from each other or being in a convoy. Finally, the actual ChannelMatrix needs

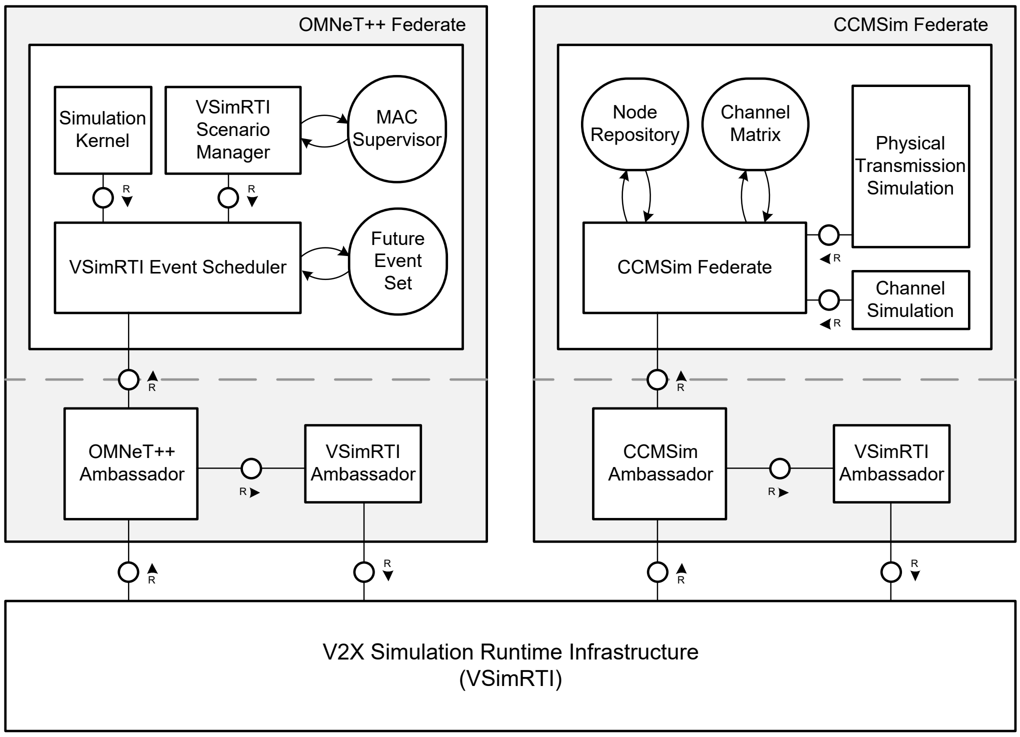


Figure 4.6: Extract of the system architecture coupling of OMNeT++ and CCMSim to the simulation environment VSimRTI

to be calculated. Since the radio channels between two nodes are reciprocal, the radio channels can be stored in a triangular matrix which brings advantages in regard to memory and performance issues. The ChannelMatrix is the basis for the Physical Transmission Simulation for all following sending attempts and is valid until the next vehicle movements are received by the CCMSim Federate. The calculated radio channels are already generated in a time-variant manner, even if positions, speeds and headings are constant until the next simulation step.

Event based Message Exchange

For the message sending procedure the Radio Channel simulation is needed two times. According to the Distributed Coordination Function in the IEEE 802.11p MAC-Layer, every node has to perform the Carrier Sense for the duration of DIFS prior to the actual transmission. To avoid unneeded requests to the CCMSim and improve the simulation time, the concept already includes an important optimization with the MACSupervisor (see Figure 4.6) which stores all ongoing transmissions. When there is no transmission at all ongoing during the sending attempt, the MAC Layer can set a self-event for the end of the DIFS duration and can then immediately access the medium. When transmissions are stored in the MACSupervisor, the detailed carrier sense and back off procedure has to be performed, using the CCMSim.

When the node sends the message over the radio channel, it first sets the transmission notification in the MACSupervisor for the following nodes which may also attempt to send a message. In the second step, the transmission is processed by CCMSim. This simulation part determines every node where the received signal strength is above the threshold of channel noise. Afterwards, the PHY Layer computes a BER for each node that could receive the message. The CCMSim PHY includes a detailed MATLAB signal processing chain of the IEEE 802.11p standard. If this BER is zero, CCMSim reports the correctly received message for each node back to OMNeT++, which in turn processes the message upwards in the communication stack and finally hands it over to the application simulator VSimRTI_App.

4.3.3 Validation

At first, it shall be validated that the coupling of the OMNeT++ MAC Layer and the CCMSim PHY Layer is working as expected. The coupling required the introduction of specific modifications in the process sequence of the original MAC Layer model. For instance, the concept with the MACSupervisor to reduce the unnecessary communication overhead between OMNeT++ and CCMSim in case of no previous transmission is one point which needs to be tested for correctness. Certainly, the whole implementation was already tested on module level, but it should be presented here in a larger scale.

Methodology

This validation experiment compares the setup of using only OMNeT++ on the one hand with the combination of OMNeT++ and CCMSim on the other hand. It is based on the metric of the Packet Delivery Rate (PDR), which is one of the most important metrics for MAC Layer assessment. The simulation comprises two distinctive cases, 1) the single access when only one sender is present and the DCF protocol can schedule the medium access directly and 2) the multi-access when more than one node have to compete for the medium-access. In either situation, the simulation shall deliver equal results for both simulator setups. Since a direct comparison between the common propagation models and the simplified PHY Layer in OMNeT++ would always produce different results as the detailed Car2X Communication Models and the PHY Layer signal processing chain in CCMSim, equal models needed to be applied. Due to this fact, the Freespace Model is implemented in MATLAB for CCMSim and is used as the propagation model in this study. In fact, the Freespace Model fits very well in the CCMSim concept. This model includes a single time-invariant radio channel with a static propagation loss according to the equation of Friis. The PHY Layer models are left unmodified.

PHY Layer Parameter	Value
Carrier Frequency	5.9 GHz
Bitrate	6 MBps
Frame Length	200 Byte
TX Power	100 mW (20 dBm)
Noise Power	-94 dBm
RX Threshold	-82 dBm

Table 4.2: Physical Layer Parameters for validation and evaluation of the advanced communication models

Accordingly, the simplified model in OMNeT++ and the signal-processing chain in CCMSim are applied.

In the whole simulation study, the communication is generally established in the way that there is one specific application (for sending messages with 10 Hz as well as for receiving). Furthermore, there is UDP used as Transport protocol, and Single-Hop Broadcasting is applied on the Network Layer to have a transparent higher layer configuration. For the lower layers, the specific models according to the IEEE 802.11p standard are used and, as already mentioned, the radio channel is simulated with the Freespace Model. Table 4.2 contains the essential parameters for the Physical Layer simulation.

Simulation Scenario

The simulation scenario bases on a straight road. Due to the introduction of the Freespace model, this straight road is in the first instance independent of the measurement campaign for CCMSim. Nevertheless, the Kantstrasse in Berlin is selected (see Figure 4.8a), which is the same scenario where the measurements for urban environments were made, and which is also analyzed in the second part of the simulation study. In the scenario, the PDR is measured for two probe vehicles, one sender and one receiver. The sender emits 10 messages per second and the receiver knows in advance when it has to expect a message from the sender. In this way, the receiver can calculate the PDR as the ratio of the received and the expected messages. As depicted in Figure 4.8a, there are two groups of each 21 vehicles approaching each other. The first group with the blue route starts on the eastern end of the Kantstrasse and includes the probe vehicle for sending. The second group with the red route starts at the opposite end and includes the receiving probe vehicle. The probe vehicles are always the central vehicles of their group.

In the single access case, only the sending vehicle is actively broadcasting messages, the receiving vehicle is receiving and all other vehicles have turned off their communication unit. In the multi-access case, the other vehicles produce

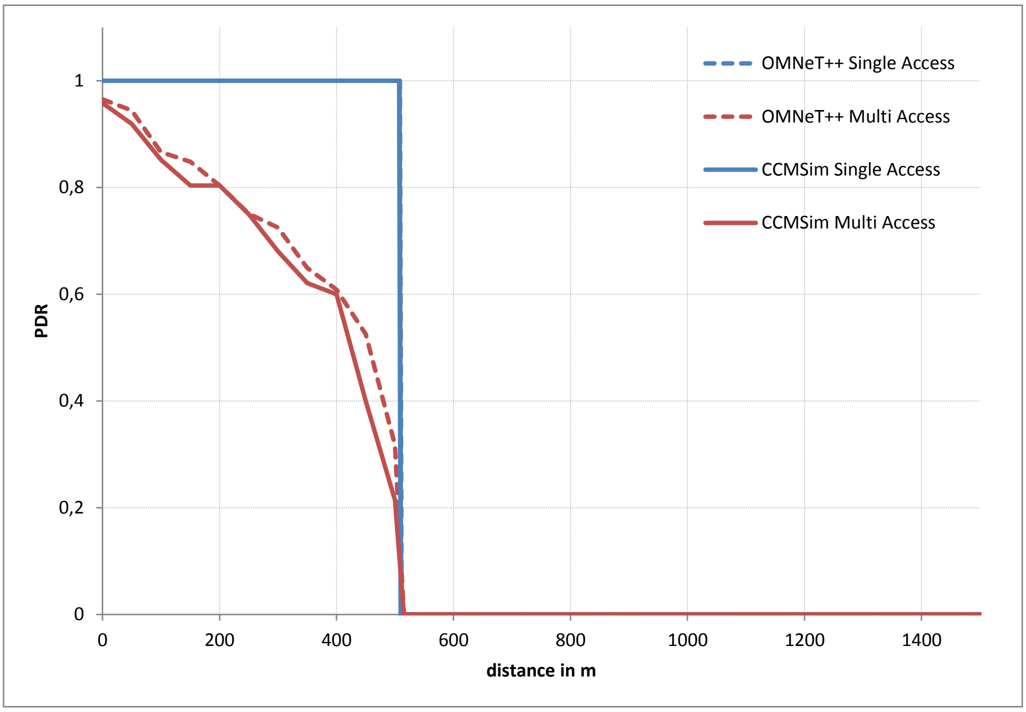


Figure 4.7: Comparison of the PDR for OMNeT++ and CCMSim in single access and multi-access case

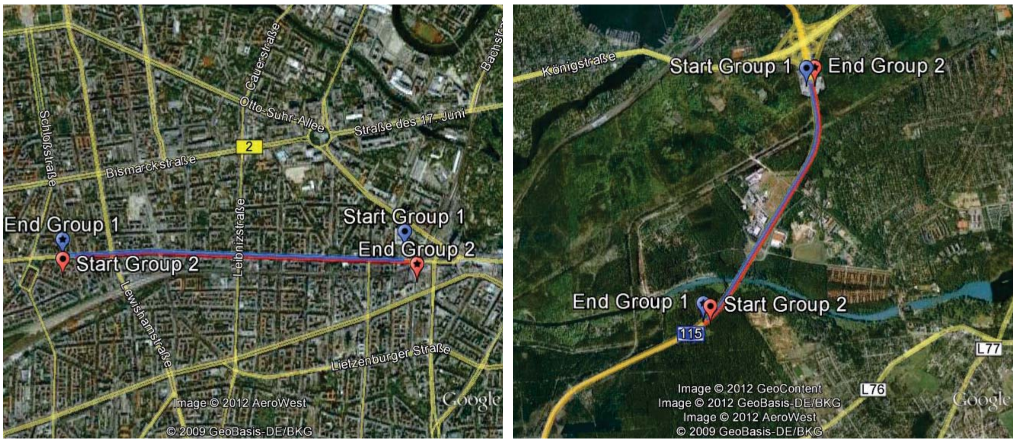
additional traffic on the broadcast medium. Altogether, 40 vehicles produce background traffic with each 10 messages per second.

Results

Figure 4.7 shows the results for the initial validation simulation. The dashed graphs depict the simulation results for the original OMNeT++ and the full lined graphs belong to the new implementation with the combination of OMNeT++ and CCMSim. The single access case is colored blue and the multi-access case red.

In the single access case, both simulator setups produced completely congruent results. The Packet Delivery Rate is 100 % up to a fixed distance of circa 509 m, which is a result of the applied Freespace model and the dedicated PHY Layer configuration from Table 4.2. At this distance, the PDR drops directly to 0 %. Obviously, it was expected to obtain exactly these results, as it is straightforward to control all parameters for this reference single access case.

In the multi-access case, the PDR contains further dependencies. The communication behavior is additionally influenced by the DCF in the MAC Layer, where the number and the position of the vehicles have a major effect. Certainly, the influences of the Hidden Terminal Effect turn out different in a case where



(a) Scenario Kantstrasse (urban) (b) Scenario Dreilinden (highway)

Figure 4.8: Simulated scenarios with oncoming traffic, visualization based on satellite map from Google Earth [Goo12])

all nodes are equally distributed in the communication range compared to the scenario where two groups of vehicles are approaching each other. Nonetheless, the results of both simulator setups are once again identical. The minor deviations result from the simplified PHY Layer in OMNeT++ and the detailed PHY Layer in CCMSim. All in all, the results prove that the implementation works correctly in either case, the single and the multi-access.

4.3.4 Evaluation

The second part of the study evaluates the influences of the detailed CCM on the general communication properties compared to the common propagation models which are already included in all network simulators.

Methodology

As in the previous study for the validation of the implementation effort, a comparison between OMNeT++ only and the new environment with OMNeT++ and CCMSim is presented. In this comparison, the focus is set on the differences, which can be modeled. To point out particularly the influences of the new channel models and the PHY signal chain, only the single access case is simulated. However, two scenarios in different environments are analyzed.

Again, the PDR is used as evaluation metric for the comparison. Additionally, the Received Signal Strength (RSS) is presented as a second important metric, since different propagation models result at first in a different received signal, which is then decoded by the PHY Layer and leads to the according PDR. For the PHY Layer chain in CCMSim, the RSS is only one parameter amongst others (e.g.

the Doppler shift), which affect the PDR. Hence, even in the single access case, a simple transformation between the RSS and the PDR is not directly possible.

The communication is established with the parameters of Table 4.2. However, this time Rayleigh Fading is applied as propagation model for OMNeT++, since it is recognized as the fundamental model to incorporate multi-path effects.

Simulation Scenarios

The simulation is performed for two representative scenarios in an urban and a highway environment.

At first, the urban scenario in Figure 4.8a is again the Kantstrasse in Berlin. Such an urban environment is characterized by vehicle driving speeds of maximum 50 km/h, but primarily stronger multi-path properties. Buildings and other vehicles have a substantial impact as near scatterers. The second scenario in Figure 4.8b is a highway section, located in Dreilinden near Berlin. Typical properties of the highway environment are the higher driving speeds of 120 km/h, which lead to a higher Doppler shift. Furthermore, fewer scatterers mean fewer reflections and multi-paths. In either scenario, the CCM are based on measured data from driving situations where vehicles are approaching each other. These situations of oncoming vehicles are therefore reproduced in either simulation.

Similar to the first simulation study, the scenario includes two groups of vehicles approaching each other. For the simulation of the single access case, only the sending vehicle with the blue route and the receiving vehicle with the red route are active in each scenario.

Results

The results in Figure 4.9 depict the statistical average values for the RSS for 10 simulation runs. With the RX Threshold (dotted gray line) and the RSS for the Freespace case (dotted black line), two additional reference lines are added to the diagrams. The RX Threshold marks the RSS value at which, according to the IEEE 802.11p standard, the PHY Layer detects the received signal as a valid incoming frame and starts the signal processing to decode this frame. The graphs for Rayleigh Fading in OMNeT++ are displayed as dashed lines and the graphs for the CCM as solid lines.

Principally, it can be seen that the graphs for Rayleigh Fading have the similar gradient as the Freespace baseline plus additional constant impairments, which result from the modeling of deep fades. Moreover, both graphs are almost equal. This can be traced back to the fact that Rayleigh Fading is not able to distinguish between different environments.

In contrast, the graphs for the CCM have a different behavior, since they are developed to consider the effect of the varying environments. The RSS is generally higher for the urban environment compared to the highway environment.

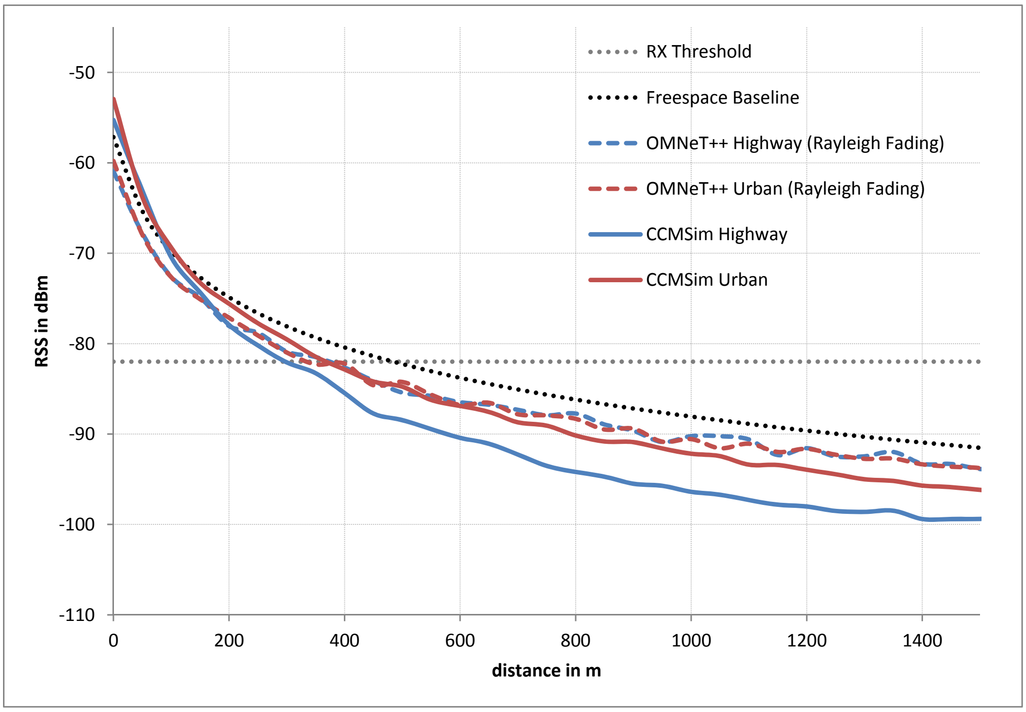


Figure 4.9: Comparison of the RSS for OMNeT++ (Rayleigh Fading) and CCM-Sim in urban and highway scenarios

The reason for this result could be the higher amount of received energy due to more multi-path components in the urban environment. Furthermore, both CCM graphs have a higher RSS at short distances up to 200 m, which decline stronger than the Rayleigh Fading. This could correspond to the fact that the line-of-sight (LOS) path is dominant when the approaching vehicles meet, and at higher distances mainly NLOS paths exist. Rayleigh Fading considers only NLOS paths and leads more pessimistic results for short distances.

Figure 4.10 shows the results for the PDR with the same color - and line style as the previous diagram. Again, the effect of the different environments is clearly visible for the CCM. Rayleigh Fading delivers the same results in both environments. Furthermore, the comparison between the RSS and the PDR illustrates clearly that a simple transformation is not directly possible. At short distances, the average RSS for the CCMs is several dB higher than Rayleigh Fading in both urban and highway. However, due to the adverse conditions with for instance higher Doppler frequencies in the highway environment, unsuccessfully decoded packets are more likely. Hence, the statistical PDR for CCM highway is never better, and it declines faster compared to the other graphs.

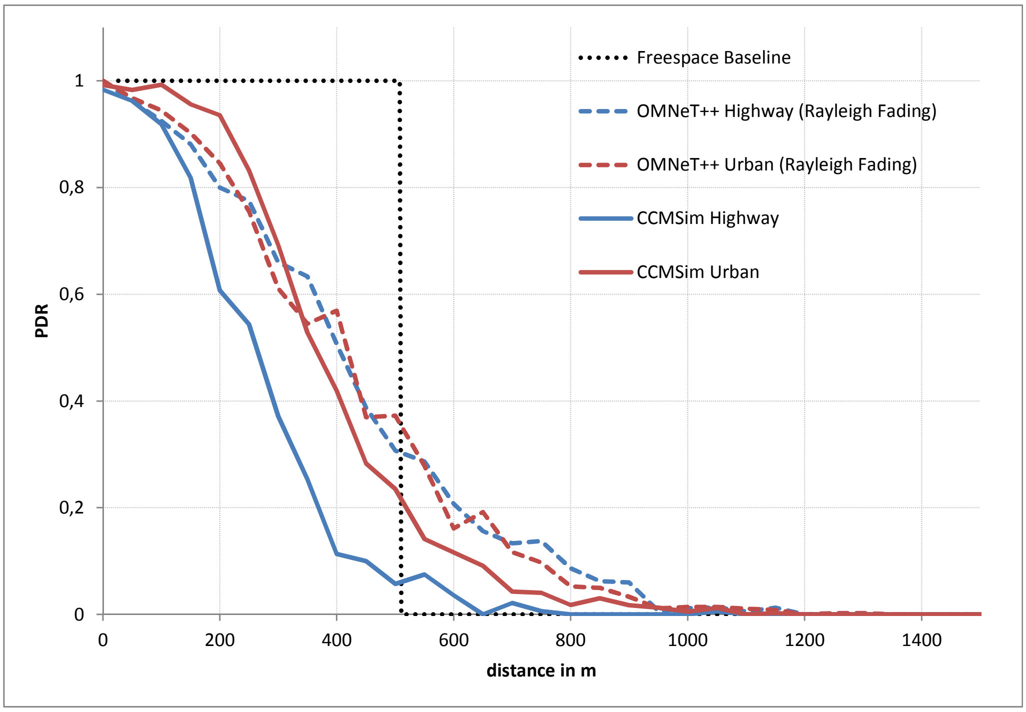


Figure 4.10: Comparison of the PDR for OMNeT++ (Rayleigh Fading) and CCMSim in urban and highway scenarios

4.3.5 Summary

This section presented how the MATLAB based simulation tool CCMSim can be integrated into the infrastructure VSimRTI to perform simulations with advanced statistical propagation models and a Physical Layer signal processing chain in a larger scale. The simulation results for the CCM clearly illustrate the differences between an urban and a highway environment. The results can be traced back to the different multi-path characteristics and vehicle speeds. Moreover, it was identified that the correlation between the RSS and the PDR is not simply linear when using the detailed PHY Layer from CCMSim, because this PHY Layer considers effects as for instance the superposition of different paths. In summary, the results confirm that it is important to consider particular details of the radio channel as well the Physical Layer transmission simulation even in larger scale. This guideline should be applied for any investigations on V2X applications.

4.4 Simulation of Cellular Networks

4.4.1 Motivation

As discussed in Section 3.3, cellular networks are comprehensive systems with a high number of entities. Moreover, these networks offer very extensive configuration opportunities to match the requirements of the according operator. These facts lead to very different characteristics of the particular systems. Hence, the simulation of cellular networks with the perspective from the applications is a challenging task.

The simulation of cellular networks is commonly divided into two different perspectives which have a different stage of abstraction. On the one hand, the link level simulation comprises the lower layers (MAC, PHY) and the radio channel. In this way, it models for instance the radio link between a NodeB to the UE. On the other hand, the system level simulation focuses on the higher layers and is used for the network view. This level considers e.g. a set of NodeBs and the associated UEs.

Nowadays, different system level simulation frameworks are proposed, concentrating on LTE cellular systems. The longest standing open source LTE system level simulator bases on MATLAB [IWR10]. In the original version, it is limited to the downlink and does not consider several important features as broadcast. The C++ based framework LTE-Sim is already very feature-rich [PGB+11]. It supports uplink, downlink, several schedulers, handover and more. The well-established communication simulator OMNeT++ is used to build up the end-to-end system SimuLTE [VSN14]. The latter concept is appealing, as OMNeT++ is already coupled to the existing simulation infrastructure. Even though some of these approaches have a detailed model base, they have several shortcomings for larger scale scenarios, which need to be addressed in this work. The simulators are more or less tied to one access technology, namely LTE. More significantly, while for simple ad hoc communication, the direct modeling approach is sufficient, for larger scale scenarios of cellular system simulation, the given simulators are too complex to configure and the detailed simulation is computationally too expensive. In contrast, trace-based cellular simulation is another promising approach that claims to be much faster than system level simulation [GKMG14]. Similar to the empirical radio propagation modeling, the trace-based technique derives models from real-world measurements. Hence, it works without particular assumptions for the network setup and configuration.

With the new simulator VSimRTI_Cell, this section presents a way, which introduces a similar grade of abstraction for cellular networks as the trace-based simulation. The core models even base on a dedicated measurement campaign. The developed simulation tool is lightweight and fast enough for larger scale scenarios. However, particularly from vehicular application perspective, the simulator also models important features, which are not regarded in the other frameworks [PMR14a, PMR14b]. The conceptual design of the VSimRTI_Cell simulator particularly regards for the following key aspects.

Technology VSimRTI_Cell is independent from the actual releases of standardized cellular access technologies such as UMTS-HSPA, LTE or even

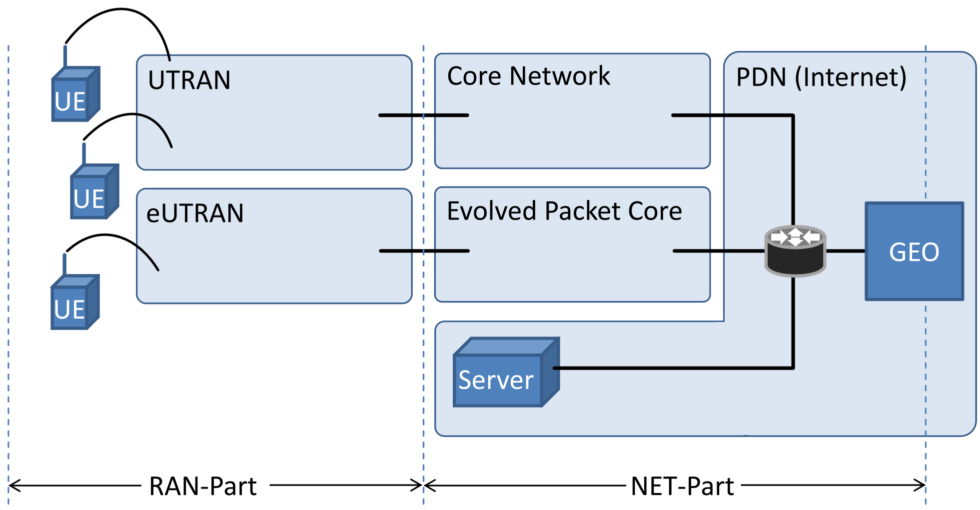


Figure 4.11: Black box assumption for the cellular system for V2X communication

5G.

Deployment and Coverage VSimRTI_Cell introduces a very flexible network deployment concept, which ranges from configuring individual cells to regions of equal coverage.

Network Load VSimRTI_Cell considers the fact that V2X communication has to coexist with data traffic generated by other users (e.g. with smartphones or surf sticks). The simulation only computes the V2X communication.

Features VSimRTI_Cell provides important functionalities for the specific needs of V2X communication. For instance, the GEO entity provides the functionality for geographic addressing and information exchange. Moreover, the implemented MBMS functionality allows simultaneous broadcasting of messages to all vehicles in a region or cell.

4.4.2 Architecture

With the named aspects in mind, the following important metrics for the network qualification are identified to be collected within an initial measurement campaign. From these metrics, suitable simulation models are developed

- Transmission delays
- Reliability towards packet losses
- Available data rates

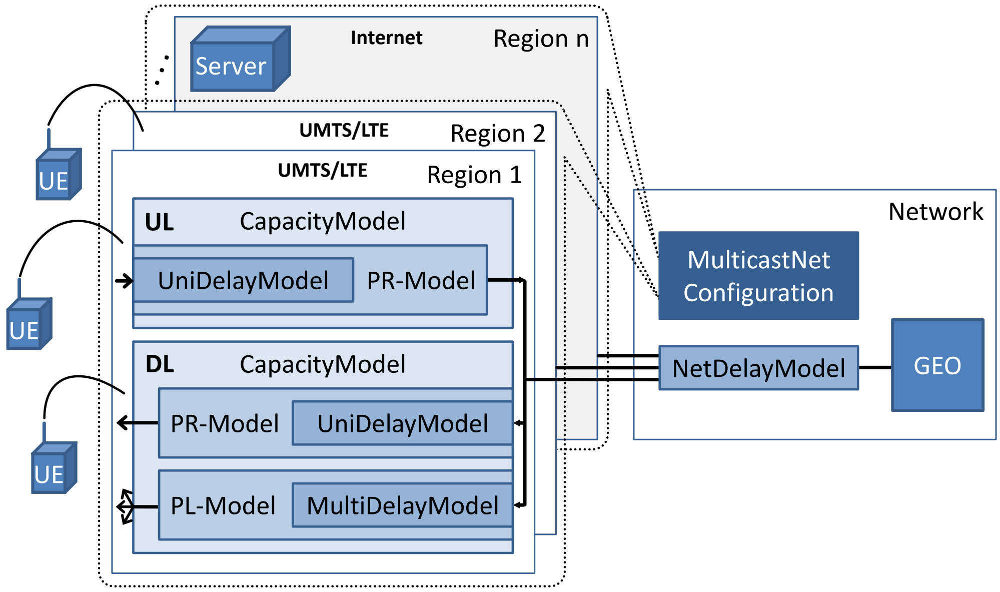


Figure 4.12: Architecture of the VSimRTI_Cell simulator

The referred measurement campaign for data collection focused on an end-to-end connection from a smartphone to a server via UMTS. This approach considers the network as a black box, without further assumptions for the specific deployment regarding the components of NodeBs, RNC, Gateways, etc. in between. Figure 4.11 depicts this general assumption for the cellular system for V2X communication. It bases on the established assumption for V2X communication via the central infrastructure. Hence, direct communication use cases with approaches as D2D are currently not considered. Beside mobile UEs and stationary servers in the PDN, the system also includes a GEO entity, which is introduced for the specific needs of Geographic Messaging in the V2X communication context. The GEO is also located in the PDN. The assumption for the cellular system separates between one part for the Radio Access Network (RAN-part) and one part for the Core Network and public data network (NET-part). The separation intends to enable a more flexible configuration of the overall system.

As the real-world measuring of the communication metrics can be a comprehensive task [GKMG14], the presented concept aims not only to use the data from the own measurement campaign, but also to allow integrating collected data from others. In this way, the VSimRTI_Cell should be also configured with data from network operators, with measurements from other researchers [WCML07, SGV$^+$09, PPHP09, TEMLP10], or with other community driven databases. Today, several projects as OpenSignal (www.opensignal.com), RootMetrics (www.rootmetrics.com), or Sensorly (www.sensorly.com) collect crowd-sourced information about the mobile network performance and coverage.

Figure 4.12 presents the architecture of the VSimRTI_Cell. The concept, first, includes multiple Regions with specific geographical extensions to create a radio access network with the according coverage properties. Every region consists of one Uplink and one Downlink module to simulate the packet transmission in the RAN-part. In this context, Uplink and Downlink always refer to the direction towards respectively from the GEO entity. For instance, a transmission from an Internet-based server towards a vehicle would include an Uplink between the server and the GEO and a Downlink between the GEO and the vehicle. While the Uplink direction only allows point-to-point communication, the Downlink supports point-to-point (Unicast) as well as point-to-multipoint (Multicast). The Uplink module is composed of the three nested models for the Delay, the Packet Retransmission and the Capacity. The Downlink module includes two individual paths for Unicast and Multicast, which share the same Capacity. The Downlink path for Unicast is composed of the models for the Delay and the Packet Retransmission as the Uplink path. The Multicast transmission needs to regard for different characteristics. In contrast to reliable ARQ-based Unicast, Multicast only employs FEC with the chance of Packet Losses. Moreover, Multicast typically exhibits a different delay based on the MBMS scheduling period. For this reason, the Downlink Multicast chain provides a separate Delay Model and the Packet Loss Model.

The second major part of the VSimRTI_Cell models the NET-part. The Network allows configuring an additional network delay. It furthermore comprises the GEO with its configuration of the Multicast regions. The GEO functionality is implemented in the VSimRTI_Cell. Finally, mobile nodes such as vehicles and stationary servers are the nodes which actually attempt for sending and receiving messages. Their application logic is implemented in the VSimRTI_App application simulator.

The following sections give further details about the Region and Cell concept, the transmission models and the functionality for Geographical Messaging.

Regions and Cells

According to the VSimRTI_Cell design aspects, the region definition aims for the flexible configuration of the cellular network deployment. In the first instance, regions are independent from and do not necessarily conform to the actual cells. Figure 4.13 depicts the possible definitions, allowed by this concept. The underlying simulation models allow for the definition of arbitrary polygons as regions. For the sake of simplicity, the configuration is presented with rectangular regions, although this would introduce a certain abstraction towards the real world characteristics.

Free definition (regions != cells). This definition typically applies for measured (trace-based) or crowd-sourced data. For instance, the named measurement

(a) Free definition (b) Exact definition

(c) Intra-cell definition

Figure 4.13: Different definition possibilities for cellular regions in VSimRTI_Cell, visualization based on map from OpenStreetMap [Ope15]

campaign collected the points for the metrics of the latency, the packet loss and the data rates mainly in connection to their position. The measuring points with equal or similar values are aggregated to the different regions. A further mapping to a certain base station is not performed.

Exact definition (1 region == 1 cell). This definition applies when network operator data about the individual base station positions and their coverage areas are available.

Intra-cell definition (n regions == 1 cell). For more detailed investigations of different coverage areas inside a single cell, the region definition also allows to e.g. configure a central region with a more capable parameter set compared to the regions at the cell edges.

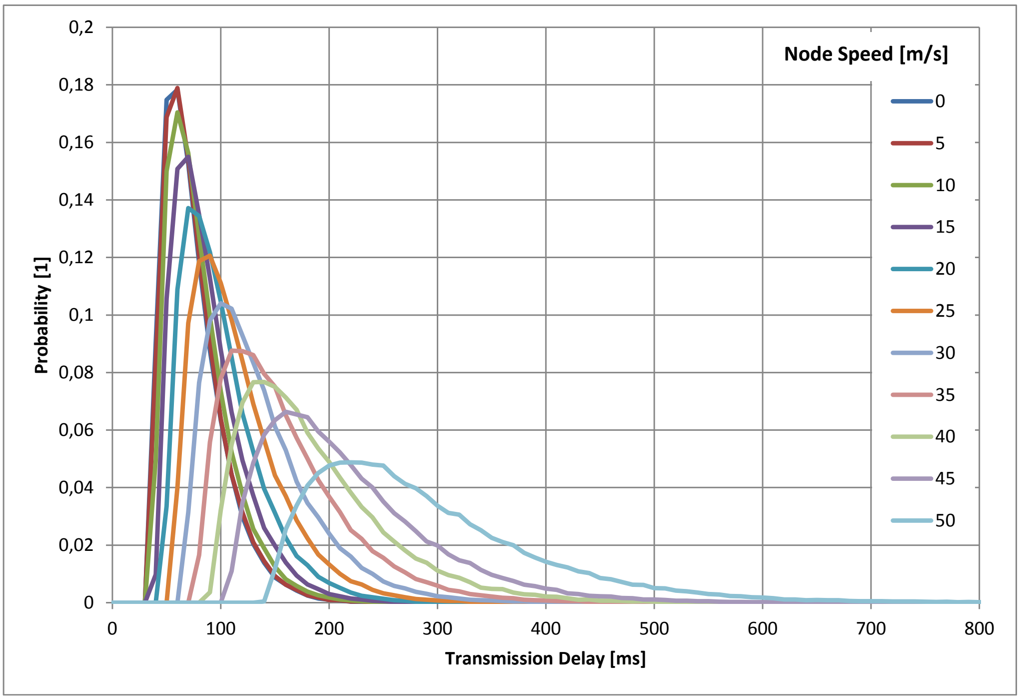


Figure 4.14: Probability distribution of the gammaSpeed delay at different speeds

For practical reasons, the region configurations need to regard for two specific situations. First, not the whole scenario area may be covered with a particular region definition, but nodes may move to an uncovered location. In this case, the global region always defines a default configuration. Second, multiple region definitions may be configured to overlap for certain locations. In this case, the configuration of the smallest region is always selected for the transmission calculation.

Delay Models

The Delay models, regardless of the employment as UniDelayModel, MultiDelay-Model or NetDelayModel, always constitute the core component for the simulated packet transmission. They support four different basic delay types to simulate the transmission time for every packet statistically.

constant is the most basic delay type of VSimRTI_Cell. It always yields the same configured delay for every sent packet. This more synthetic model is mainly intended to be used for debugging or primary clarifications. Moreover, it can model a constant offset for the NetDelayModel.

simpleRandom extents the constant delay type. It defines a minimum and maximum bound for the delay (*minDelay*, *maxDelay*) and a possible number of discrete *steps* (n). With this configuration, the simpleRandom type randomly generates n different uniformly distributed delays in the interval $[minDelay, maxDelay]$.

gammaRandom addresses the particular characteristics of the RAN-part. The measurement campaign identified that the distribution of the transmission delays in a real-world environment sufficiently conforms to the Gamma distribution. This delay type allows to configure the minimum and the expectation value of the delay (*minDelay*, *expDelay*).

gammaSpeed is the most sophisticated delay type. It bases on the gammaRandom type and also includes impairments for higher vehicle speeds according to a fitting of the measurements from the campaign. Figure 4.14 displays the probability distribution for the gammaSpeed delay type at different speeds with the measured values of $minDelay = 40\ ms$ and $expDelay = 80\ ms$ for a representative set of HSPA transmissions. According to this diagram most packets have a delay between 50 ms and 200 ms. However, this is only one possible parameterization and this type also qualifies for the modeling of other mobile network generations as HSPA+, LTE or even 5G.

PR-Model and PL-Model

The PR- and the PL-Model address the effect of individual packet transmission impairments between the node and the base station due to inappropriate signal coverage. However, when a reliable connection with ARQ is assumed, no packet is effectively lost, but retransmitted. This is in turn connected with an additional delay. Hence, the Packet Retransmission Model is particularly employed for the reliable Unicast transmissions in Up- and Downlink. For the Broadcast communication in Downlink, where only FEC can be applied, the Packet Loss Model simulates complete packet drops.

The configuration of the coverage quality parameter between 0 and 1 determines the probability of a retransmission (PR-Model) or a packet loss (PL-Model) for each transmission attempt. In case of a packet loss with or without retransmission, the packet will always occupy the channel resources even for unsuccessful transmissions. The parameter value of 0 implies an unimpaired transmission for each model. A value smaller 1 gives the probability of loss or retransmission in percent. A value of exactly 1 leads to a packet drop in each model. This behavior can be employed to account for entirely disconnected regions in tunnels or shadowed urban canyons. However, the PR-Model optionally reports a packet drop notification to the sender node to consider a reliable transport protocol such as TCP.

Capacity Model

The Capacity Model considers the channel load of a region and calculates the final delay for the individual packets. With the configuration parameter of the maximum available capacity for all simulated nodes, it allows investigations which are independent of the family and the generation of the mobile access technology. Furthermore, it respects static data traffic caused by other mobile users with smartphones, surf sticks, broadband cards. This is an important feature as V2X communication needs to share the resources with other applications. For these reasons, the region definition is particularly important for this model. For example, assume a network deployment with equal capacities in different cells. When this deployment is configured with regions of different size, the capacity needs to be adapted to the region size.

The second parameter for this model is the maximum user bit rate, which resembles the peak speed from the according user data plan. It is still possible to serve more simulated nodes in a certain region than the ratio of the available capacity divided by the maximum user bit rate. When every user demands its maximum bit rate, the result would be that the network gets congested locally and not every sender can transmit directly. Exactly this effect is modeled, when the sending user reserves the resources for the packet over the time of the transmission.

The Capacity Model maintains a resource map where all reservations are accumulated for their time span. When a new sent packet exceeds either the maxNodeBitrate (the data plan limit is reached) or the available capacity (the network is congested in this region), the packet needs to be queued and thus further delayed until the channel is free again.

Topological and Geographical Messaging

The GEO entity in the Net-part of the VSimRTI_Cell provides functionalities for different addressing schemes. In a real core network deployment, these functionalities would be distributed over several entities, as for instance in LTE the MME for node mobility management. The GEO is connected to all regions via the NetDelayModel to simulate an additional delay through the Net-part (Core Network and PDN). During simulation runtime, the GEO follows the node mobility. It maintains a table with the node positions and the mapping to the corresponding region. Every sent message in the Uplink goes through the GEO, which distributes the message in Downlink either for point or multipoint reception.

For conventional data traffic, the addressing between the nodes is realized by IP and involves multiple entities in the core network. The simulation can abstract from several aspects of a real core network. However, the user mobility and the router functionality, which are covered by the SGSN in UMTS or the MME and SGW in LTE, need to be regarded at least. On that account, the GEO uses the knowledge of the current node positions to forward the messages into the Downlink transmission chain of the according region of the destination node. Many V2X communication use cases envision geographic messaging over cellular networks, similar to geographic ad hoc routing. For this purpose, the IP address is extended with the definition of the geographic destination area. The GEO translates the address to direct the packet to the according nodes.

Moreover, many V2X communication use cases demand the dissemination of the same information to multiple nodes in the area. Hence, they are a prime example for the utilization of MBMS and eMBMS (MBSFN) features to allow efficient and resource saving broadcast transmission. Depending on the MulticastNet configuration, the GEO provides transmission modes similar to MBMS and MBSFN. The MulticastNet configuration defines which regions together form a compound for broadcasting or multicasting a packet. The GEO replicates the packet to be sent in every region compound covered by the destination area.

4.4.3 Simulation Study

The investigation of automotive media streaming applications is a prime example to demonstrate a broad set of the introduced features of VSimRTI_Cell. The rising popularity of music on demand and media cloud storage services pushes automotive manufactures efforts to provide decent music streaming capabilities in vehicles. However, with the increasing usage of music streaming services in cars, it is getting harder for the service providers to balance the network load. This issue arises from the fact, that the mobile network will be easily exhausted in crowded areas with many users listening music in their cars and so users will experience certain usability drawbacks. Another important issue that needs to be addressed in order to ensure music streaming quality in cars is implied by movement characteristics of cars. Especially in urban environments, cars need to pass areas of bad reception imposed by the street infrastructure like tunnels, underpasses, or street canyons, which might lead to network interruptions. On highways, due to the high traveling speed, frequent handover between cells may lead to connectivity interruptions. In rural areas, totally disconnected regions can cause network loss for longer periods.

Media Streaming Applications

The two issues, network overload on the one hand and network interruptions on the other hand, need to be addressed for music streaming in cars in the future. Smart prefetching algorithms enable the reduction of the download overhead and the reasonable allocation of the network capacity. Relevant information that can be used to implement such prefetching is only known to the music streaming clients inside the cars. This information includes:

Music content The order, the length, and the size of music titles the user most likely wants to listen to, which can be e.g. derived from personal playlists.

Dead zones The locations of bad reception imposed by the road infrastructure, e.g. tunnels, which are located on the current route the vehicle is driving on.

Crowded zones The information regarding areas of regularly low available capacity due to heavy network load, derived from crowd sourced data. This data can be empirically collected by sharing connectivity and coverage information among users.

What smart prefetching basically needs to achieve is to use these information sources in order to: First, determine which music titles the user is likely to request at which point in time and so estimate when this title needs to be downloaded completely. Second, estimate the available capacity along the current driving route considering all dead and crowded zones, and schedule the download requests accordingly. In this way, crowded areas are relieved, dead zones are bridged, and download overhead is minimized.

The prefetching strategies run in a decentralized manner on the individual vehicles. Yet, the goal of such algorithms cannot be achieved in a way of selfish optimizing, but by aiming on the global optimization. The simulation with VSimRTI_Cell qualifies to assess the effect of the algorithms on a large amount of users, their mutual influence, and the impact on the global network usage. In the presented simulation study, the developed Smart Prefetching approach is compared with two well-known streaming algorithms referred to as Greedy and Constant Buffering.

Greedy Buffering always buffers as much as possible, which grants a high buffer level to bridge large dead zones, however has a high impact on the available capacity and the download overhead.

Constant Buffering buffers up to a defined limited buffer size in order to reduce the amount of downloaded data and have a low impact on the available capacity, however grants a low buffer size to bridge dead zones. The evaluated implementation always maintains a buffer for 30 s in advance.

Smart Prefetching requests content according to the assumed user needs, which is expected to have a lower impact on the capacity and download overhead, while still provide enough buffer size to bridge dead zones.

Greedy Buffering and Constant Buffering are very basic approaches, which are well-known in the field of multimedia streaming. Smart Prefetching introduces the new aspect of improving the buffering approach by using situational information

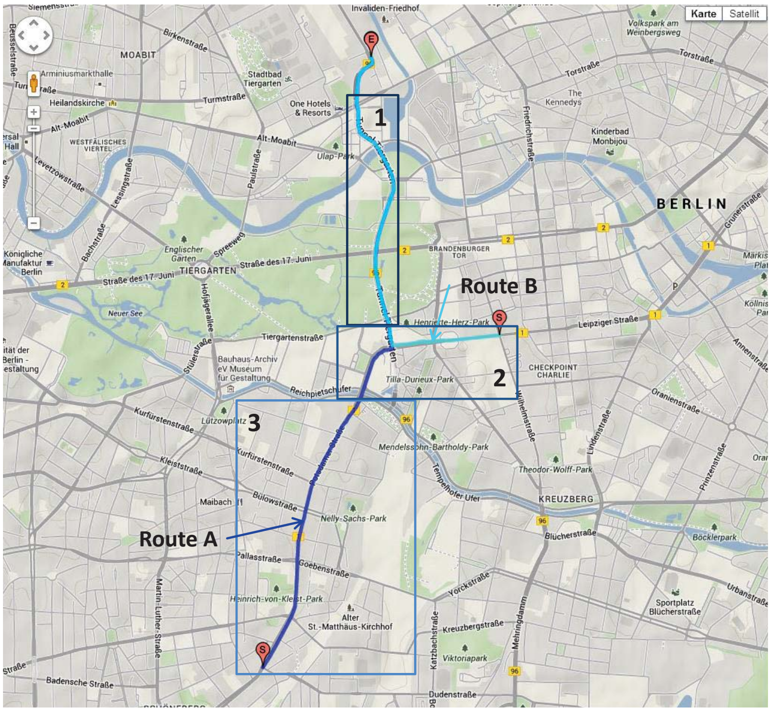


Figure 4.15: Region definition and vehicular routes in the simulated scenario for the media streaming use case, visualization based on map from Google Maps [Goo13]

regarding the music content, dead zones, and crowded zones to optimize the buffer fill level.

Simulation Scenario

The simulation scenario is located in an urban setting in the center of Berlin. It is displayed in Figure 4.15. This scenario defines three regions with different configurations concerning the mobile network characteristics. The Tiergartentunnel has no sufficient network coverage. Hence, region 1 is configured as a void area with a $prValue = 1$ for the Packet Retransmission Model. The region 2 south of this tunnel around Potsdamer Platz provides already an excellent coverage, but typically gets crowded during rush hours. This means that the number of other users to compete for the overall capacity is very high, which results in a reduced available bandwidth for simulated vehicles. The region 3 in Schöneberg is already outside the center and less crowded, while still covered very well. During the simulation, vehicles on two different routes join before the tunnel. The vehicles on route A start in Schöneberg (region 3), head northbound through region 2 and finally pass the Tiergartentunnel in region 1. The origin of vehicles on route B is the Potsdamer Platz in region 2. After a right-turn the vehicles on this route immediately enter the tunnel in region 1. All vehicles in the simulation are covered

Region	**1**	**2**	**3**	**4** (wired)
Bandwidth	100 Mbit/s	10 Mbit/s	10 Mbit/s	1 Gbit/s
PR	0	0	1	0
DelayModel	gammaSpeed	gammaSpeed	gammaSpeed	constantDelay
minDelay	40 ms	40 ms	40 ms	1 ms
avgDelay	150 ms	150 ms	150 ms	1 ms

Table 4.3: Simulation parameterization for the different regions in the media streaming scenario

by the regions 1 to 3. Furthermore, the media server that delivers the streaming content to the vehicles is also simulated by the VSimRTI_Cell. It is placed in a separate fourth region, which is connected with very good network properties comparable to high speed wired network connection. Thus, solely a short constant delay of 1 ms is added to the connection on this link. Region 4 is not included in Figure 4.15, since the media server is not necessarily located in the simulated area (Berlin). Table 4.3 summarizes the overall simulation parameterization.

The prefetching algorithms are tested in two separate simulation series. In the first series, 10 vehicles are equipped with an audio streaming application to request one single music playlist with a compression of 320 kbit/s according to the algorithms Greedy Buffering, Constant Buffering, and Smart Prefetching. During the simulations, no user triggered switching between titles within the playlist, nor between different playlists takes place. The music compression rate already stands for a high quality streaming service. However, with few vehicles the network capabilities should be sufficient. The second simulation series increases the number of vehicles to 40 in order to reach the capacity where straightforward downloading is not possible anymore. In each case, 10 and 40 vehicles, half of the vehicles drive on route A and the other half on route B, respectively.

The intention of the described scenario and the corresponding simulation parameterization is to create the following situation. In the tunnel (region 1), there is no network access, i.e. in order to be able to playback music, the vehicles need to reach a sufficient download buffer level before entering the tunnel. The vehicles starting on route B in region 2 have little time to fill their buffers on their short route to the tunnel entrance. Region 2 is parameterized to provide barely enough capacity for the vehicles on route B to fill their buffers on time. For this reason, the vehicles approaching on route A need to fill their buffers earlier in region 3, in order to relieve region 2 and grant the full capacity there to the vehicles on route B. This setup represents a situation in real world, when there is potentially enough capacity available averaged through the overall scenario, yet a simple straightforward downloading should fail. To solve that, both aspects, the tunnel and the low capacity zone, need to be taken into account.

Algorithm	Greedy	Constant	Smart
Data volume (10 veh)	40.96 MB	19.31 MB	31.07 MB
Data volume (40 veh)	42.14 MB	21.91 MB	32.83 MB
Playback delay (10 veh)	12.13 s	137.49 s	19.79 s
Playback delay (40 veh)	123.92 s	141.78 s	95.29 s

Table 4.4: Simulation results for the three presented prefetching algorithms

The impact of the three different prefetching algorithms is compared by the means of the user experience and the network utilization. Obviously, the optimal algorithm is intended to provide a high user experience while generating a low network load. The network load is measured by the amount of data, which is downloaded during the simulation. The user experience is measured with the metric of the media buffer underruns. More specifically, the buffer fill level is evaluated over the time. The user experience itself is then deemed as impaired when the buffer is empty and prevents an instant playback. The resulting playback delay is accumulated over the whole simulation time. As additional metrics for the non-functional aspect of user acceptance, the number and the duration of buffer underrun incidents are evaluated. From users' perspective, it does make a difference how often and how long the music stream is interrupted due to buffer underruns. For instance, a user might accept one delay of 5 s, but not 10 delays of 0.5 s in a row. For this reason, the number and the duration of buffer underruns is a relevant metric for the assessment of prefetching algorithms.

Simulation Results

Table 4.4 presents the results for the average values for the data amount and delay caused by buffer underruns. The results are separated for the simulation series with both 10 and 40 vehicles.

Concerning the data volume the Greedy Buffering requires the highest load, while Constant Buffering is very thrifty and Smart Prefetching is intermediate. Moreover, a comparison of the simulation series with 10 and 40 vehicles shows that the data amount can still be served in the case of 40 vehicles, i.e. the region coverage properties are not too restrictive. However, especially for the Greedy Buffering the resource usage is no longer distributed fair enough to ensure a good user experience for all vehicles. While for few vehicles the playback delay for the Greedy Buffering delivered very good results, it increases for all users in the case of 40 vehicles. For Smart Prefetching, the delay does not increase as strong. For Constant Buffering, the playback delay is equally high in either case (10 and 40 vehicles). This preliminary result should be assessed with a more detailed evaluation of the buffer underruns in the diagrams shown in Figure 4.16, 4.17 and 4.18.

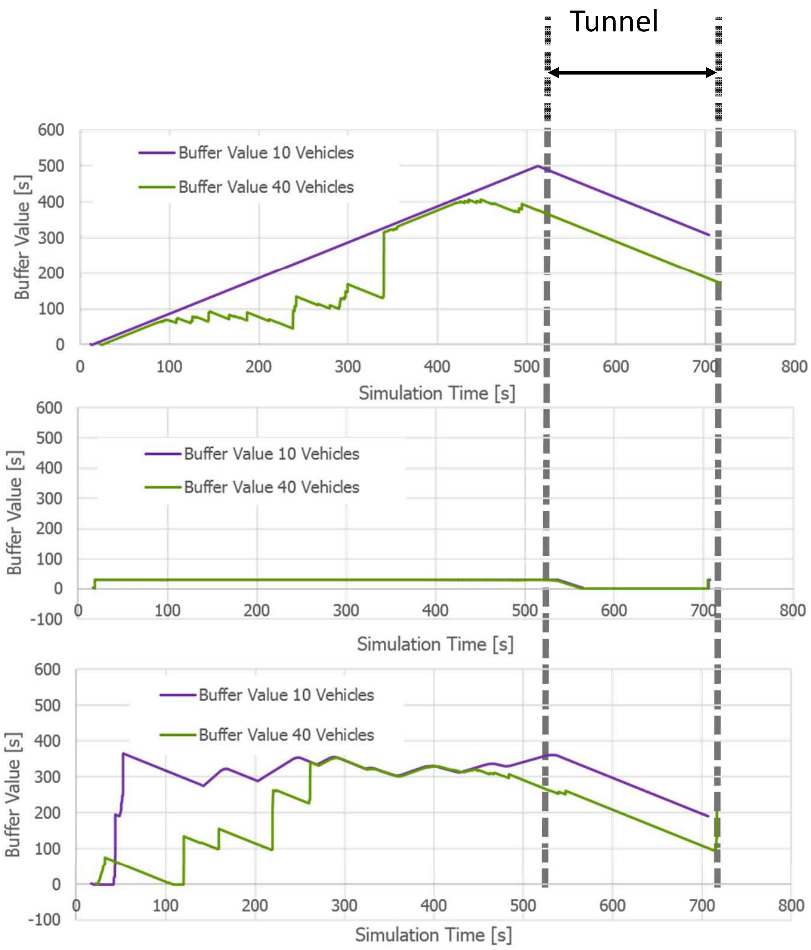


Figure 4.16: Simulation results for the playback buffer level, compared for the three prefetching algorithms - (top) Greedy, (mid) Constant, (bottom) Smart

Figure 4.16 depicts the playback buffer level in seconds over simulation time for one representative vehicle per simulation run. Consequently, buffer underrun incidents occur when the buffer level is zero. These incidents are presented in Figure 4.17, where red areas mark the locations on the routes where the buffer underrun occurred. “Constant 10/40 Veh” marks all buffer underruns of the two simulation runs with 10 and 40 vehicles for the Constant Buffering, since this algorithm exhibits the same characteristics in each scenario. “Greedy 10 Veh” marks all buffer underruns of the simulation run for Greedy Buffering with 10 vehicles, and “Greedy 40 Veh” with 40 vehicles, respectively. The same scheme applies for “Smart 10 Veh” and “Smart 40 Veh” as results of the simulation runs for Smart Prefetching.

The Greedy Buffering statically requests the audio stream without knowledge of the different network capacities. The rate is configured to be twice the rate which would be needed for real-time playback. In the case of few vehicles, the

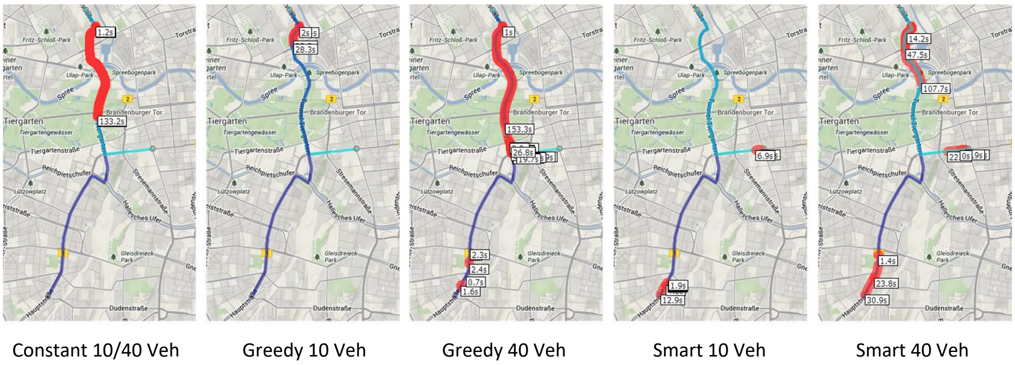


Figure 4.17: Simulation results for the buffer underrun localization, visualization based on map from Google Maps [Goo13]

requested data can be immediately served. Hence, the buffer level increases linearly. With more vehicles, the requested data rate cannot always be delivered. In the tunnel region, no further data can be delivered and the buffer level reduces again. The occurrence of the buffer underrun for Constant Buffering is quite deterministic. At the tunnel entrance, the buffer is always filled to be able to playback 30 s without further download. Consequently, the playback always discontinues at almost the same location inside the tunnel. The Smart Prefetching dynamically adapts the requests. For this algorithm, the buffer at the tunnel entrance exhibits a smaller level than the Greedy Buffering but it is nevertheless sufficient for an underrun free playback.

Figure 4.18 depicts the number of the buffer underrun incidents for Greedy Buffering and Smart Prefetching of the simulation series with 40 vehicles according to their duration. The accumulated incidents of vehicles driving on route A and route B are represented by separate bars for Greedy Buffering and Smart Prefetching, classified according to their related duration range. For instance, for Greedy Buffering there are 32 incidents with a duration between 0 and 1 s, while for Smart Prefetching there are 9 incidents in the same duration range. For the direct comparison of Greedy Buffering and Smart Prefetching, Figure 4.18 shows that Smart Prefetching has a considerable lower number of buffer underrun incidents with a duration between 0 and 10 s. This range is the most relevant when it comes to user acceptance, since up to 10 s the user is most likely to wait until the delay is over. For longer delays the user is more likely to switch to another music source like regular radio stations. Thus, the quality of music streaming was better with Smart Prefetching than with Greedy Buffering. In the range from 30 s Greedy Buffering and Smart Prefetching perform roughly equally bad. The high number of delays longer than 30 s is due to the parameterization of the simulation setup, which leads both algorithms to their limit. However, in contrast to Greedy Buffering, with Smart Prefetching the delays are equally

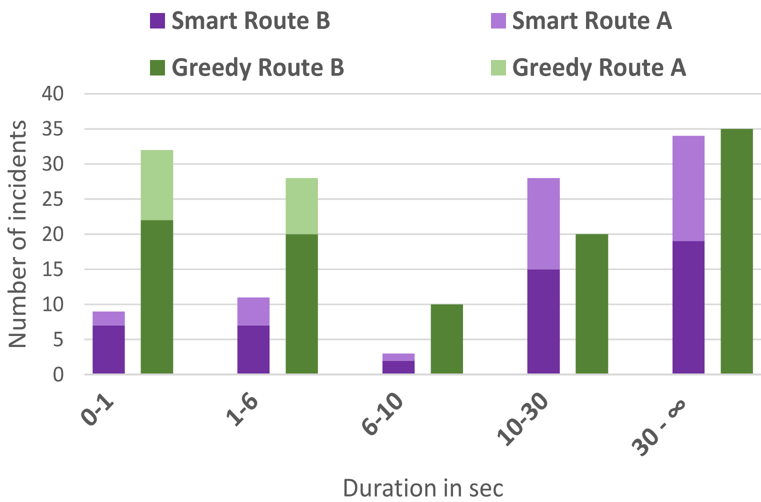


Figure 4.18: Simulation results for duration of buffer underrun incidents

distributed between the vehicles driving on both routes. In the range between 10 and 30 s, Greedy Buffering performs better than Smart Prefetching. It is caused by the fact that the implementation of the smart algorithm has still room for improvements regarding the consideration of predictable stand still times at traffic lights. This issue needs to be addressed in future work on this topic.

4.4.4 Summary

This section introduced the new cellular communication simulator VSimRTI_Cell, which particularly focuses on simulating the transmission delay through the wireless and wired parts of the cellular networks. It regards for possible packet losses and available data rates. With the implemented communication models, VSimRTI_Cell is independent of the actual standards of the access technologies. It offers the feasibilities to consider different network deployment and coverage conditions as well as additional network load originated by external cellular users. The simulation study on automotive media streaming algorithms compared conventional streaming strategies with a smart prefetching algorithm, which makes use of additional knowledge of network coverage information and the vehicles own route. In this way, it can dynamically request the media stream and conserve the mobile network capacity, while still providing a decent user experience. In summary, the study proved that VSimRTI_Cell is an adequate tool for evaluations from vehicular application perspective.

4.5 Summary of Simulation Environment

All in all, this chapter presented the necessary extensions for the simulation environment VSimRTI to be prepared for the simulation study on V2X communication in heterogeneous networks in the next Chapter 5. The model improvements of the radio propagation and Physical Layer characteristics for ad hoc communication are important for more realistic simulations. It was proved that the most prominent challenges for the operation of V2X applications result from the limited communication range and the lack of deterministic quality of service of the underlying ad hoc system. The information transmission over cellular networks with its distinctive benefits could complement the ad hoc approach. However, the high complexity and configurability of cellular networks poses certain difficulties for the simulation modeling. The novel simulator VSimRTI_Cell overcomes these issues as it introduces a suitable grade of abstraction for the cellular network. This tool is lightweight and fast enough for larger scale simulations. Moreover, it supports particular features as Geo addressing and MBMS, which are important for many V2X applications. As a result of all implementation efforts presented in this chapter, the VSimRTI simulation framework does not only allow to simulate either ad hoc or cellular networks in isolated scenarios. It actually enables the investigations where both technologies are combined in an intelligent way in an integrated scenario. Such a simulation study will be performed in the following Chapter 5.

Chapter 5

Simulation Analysis

This chapter consolidates the findings from the previous parts and presents the final simulation analysis. The first part will describe the application specific metrics. The setup will be presented in the second part. Finally, the simulation results are discussed.

This simulation study shows one solution where ad hoc and cellular communication will be combined in one scenario to support the information exchange of V2X applications over heterogeneous networks. The possible solutions for further development and employment of the technologies are co-existence, where data exchange is strictly separated to different technologies by services, and convergence, where both technologies are integrated into one network. Convergence in turn, could be enabled on different levels and on different layers of the communication stack. The presented solution aims for convergence on the application layer [PSR17]. To regard for a general statement on the communication performance, this evaluate will not only address a single application. Therefore, the used metrics are application layer metrics, which are significant for a broad spectrum of applications.

5.1 Evaluation Metrics

The application - and hence the communication performance in the simulation scenario should be evaluated with two distinct metrics.

5.1.1 Safety metric

For safety use cases, it is particularly relevant that the periodically transmitted information (in CAMs) reach the destined receivers in time. The Consecutive

CAM Period (CCP), which was introduced as communication metric in Section 2.2 in Equation 2.2, is able to measure exactly this requirement during individual situations with dynamic changes regarding the communication properties [PSR14b].

According to this definition the CCP depends initially on the sending rate f_s of the CAMs and the communication quality, which is actually the property that should be measured. In case of ad hoc communication with single hop broadcast of messages to the neighbors in the communication range, packet losses due to fading or shadowing would lead to an increased CCP compared to the sending rate. Hence, the CCP is qualified to measure burst errors. In case of communication over a cellular network, packet losses are mitigated through methods of (hybrid) ARQ with message retransmissions on the different layers. However, higher transmission latencies than the sending rate may be the result and in turn out-of-order delivery for the individual packets. The CCP is also qualified to measure this case, which leads to an increased CCP as only the freshest updates are useful for the safety applications.

With the given definition, the sole CCP inhibits some minor drawbacks. First, the range of the CCP is in the interval of $[\frac{1}{f_s}, \infty)$. Particularly the case of high values of the CCP, when the potential receiver never receives updates from the sender, could have two reasons. It could either depict critical burst errors. However, the two nodes could also be located far away from each other to be anyway out of communication range and thus most probably also out of mutual relevance. Second, the CCP actually measures the supported real-time capability for the certain use cases and the use cases could have very different requirements towards this reaction time.

Hence, the evaluation of the CCP should primarily consider all CCP time spans t_{ccp} where the node i is in the relevance area t_R of a regarded sender and where the t_{ccp} is smaller or equal than the real-time requirement τ plus a short time difference δ_t. This short time difference accounts for tolerable jitters in the message transmission. The Safe Time Ratio (STR) results when this value is normalized with the time span where the nodes are in the relevance area. It is described in (Equation 5.1).

$$STR_i(\tau) = \frac{\sum \{t_{ccp}(i) | t_{ccp}(i) \in t_R \wedge t_{ccp}(i) \leq \tau + \delta_t\}}{\sum t_R} \tag{5.1}$$

The name Safe Time Ratio (STR) was also coined in related work [SBJ+14]. With the definition of the STR to regard all measures less or equal than a specific value it shows similarities to the calculation of cumulative distribution function (CDF) of the distribution of the CCP. Actually, the complementary CDF is used in literature for the measurement of unreliable periods [KGHS12]. Furthermore, the T-window reliability gives the probability that at least one message from the considered neighbor is received during a tolerance time window T [BK06]. Accordingly, T indicates the delay requirement of the given CAM based safety application. For the identification of unreliable periods, the complementary CDF can be used [KGHS12].

Besides, the regular information refresh can also be measured with a slightly different metric, the number of Invisible Neighbors [LP11]. It is the number of nodes that are in the vicinity of an ego-node, but their periodic messages have not been received within a certain time-frame. According to this principle, the Awareness Quality calculates the ratio of visible neighbors to all neighbors [SL11].

5.1.2 Efficiency metric

Due to a higher distance horizon towards the traffic situation, efficiency use cases have more delay tolerant characteristics. The quality of information reception could be calculated with a mean squared error metric regarding the received information, according to Equation 5.2. This metric considers the deviation of the perceived information data $\hat{D}(i)$ at the individual vehicle node i in comparison to the data of the actual reference situation D. For better scalability, the MSE is normalized with the norm of the reference data D.

$$MSE_i = \mathbb{E}\left[\frac{1}{\|D\|^2}\left\|\hat{D}(i) - D\right\|^2\right] \tag{5.2}$$

For the simulated applications, the current speed from the transmitted CAMs as well as Floating Car Data (FCD) messages as represent the parameter of the information. For the simulation, the reference data D directly depends on the generated mobility pattern from the traffic simulator.

5.2 Simulation Setup

One particular aim of the simulation is the presentation of the features of our introduced cellular simulator VSimRTI_Cell [PMR14a]. Thus, this simulator is part of the simulation setup. In general, the setup includes the following simulators for the different domains:

Traffic The microscopic traffic simulator SUMO [KEBB12] simulates a realistic mobility pattern for the vehicles in the scenario.

Application The VSimRTI internal simulator VSimRTI_App serves as a data generator for the communication messages and hosts the application logic for message reception and maintaining of a local dynamic map (LDM).

Ad hoc communication The network simulator OMNeT++ simulates the IEEE 802.11p based communication stack and realistic radio propagation with fading and shadowing characteristics, introduced in Section 4.2.

Figure 5.1: Simulation scenario with routes of individual vehicles and cellular regions, visualization based on map from OpenStreetMap [Ope15]

Cellular communication The VSimRTI_Cell simulator, introduced in Section 4.4 will simulate the transmission over the cellular network.

5.2.1 Traffic Simulation

The scenario to be simulated is depicted in Figure 5.1. It is located in an inner-city environment in Berlin (Germany). The scenario includes overall 30 reference vehicles to be equipped with the applications and the communication technologies. Only these reference vehicles are considered for the result evaluation. The vehicles are spawned into the simulation on ten different routes, whereas the routes could partially overlap. This means on each route at least three vehicles enable a sufficient grade of measurement coverage. The vehicles do not perform any reactions to the traffic situation like changing their route. The main intention is to drive their route and exchange information.

5.2.2 Application Simulation

The application logic is separated into three individual parts to be deployed on the vehicles and one application for a traffic efficiency server in the internet. However, the simulated applications will not influence the traffic behavior with active route changing or similar actions.

VehicleMainModule implements the basic application facilities and should be equipped on the vehicle in every variation. It collects the sensor and location, speed, heading data to be included in the CAMs. Moreover, it maintains the LDM from sensor data as well as received messages from the ad hoc and cellular network. More specifically, the LDM implements a data matching of the information to a grid with geographic pixels. The LDM facility is first the entity that enables the transfer of periodically updated information (e.g. to support safety use cases) into time tolerant information (e.g. to support use cases with a greater overview). Second, the LDM is the pivotal point to connect the information from ad hoc and cellular communication.

VehicleAdhocModule uses the data from the VehicleMainModule and communicates the data via IEEE 802.11p. It implements two different messages to be periodically disseminated. The CAMs only include the freshest local sensor data. The FCD messages summarize the information in the LDM and map them to the central point of a geographic pixel before dissemination. Thus, it has two main parameters for the regular sending period of the CAMs and the FCD messages.

VehicleCellModule is the analogous component to the VehicleAdhocModule to communicate over the cellular network. This module supports an additional configuration for the local CAM destination area to be processed by the GEO in the cellular network. Moreover, it additionally sends CAMs per unicast to the Traffic Server. However, this application does not send FCD messages as they are management centrally by the ServerModule.

ServerModule is the application on the server and maintains a central map with the same configuration as the LDM. It collects traffic information of the CAMs from the registered vehicles and periodically disseminates FCD messages back to the vehicles.

Table 5.1 outlines the specific configurations for the most important parameters of the individual application modules. Some parameters apply for multiple application modules.

Parameter	Application Module	Value
LDM Grid Size	VehicleMainModule, ServerModule	20x20 pixels
LDM Pixel Sidelength	VehicleMainModule, ServerModule	200 m
CAM Interval	VehicleAdhocModule, VehicleCellModule	100 ms
CAM GeoRadius	VehicleCellModule	695 m
CAM2ServerInterval	VehicleCellModule	1 s
FCD Interval	VehicleAdhocModule, ServerModule	10 s

Table 5.1: Simulation parameters for the application modules

5.2.3 Communication Simulation

The communication networks are simulated by OMNeT++ (ad hoc) and VSimRTI_Cell (cellular).

OMNeT++ uses the advanced communication models for the site-specific propagation, particularly shadowing characteristics [PSR14a]. Moreover, OMNeT++ simulates the IEEE 802.11p based communication stack with the parametrization from Table 5.2. The given models for MAC and PHY layer respect for all important aspects as hidden terminals.

VSimRTI_Cell simulates the different cellular regions, depicted as black rectangles in Figure 5.1. The region locations and expansions conform to data from OpenCellID (http://opencellid.org). All regions possess equal parametrizations for the communication properties. The configuration is presented in Table 5.2. It assumes an up-to-date HSPA network with capacity and delay properties to be in-line with recent measurements [SGV+09, PPHP09, TEMLP10]. The Traffic Server is located in a specific region with the properties of the overall network to simulate a well-connected Internet server.

5.2.4 Simulation Variations

The subsequent simulation series investigates three different scenarios where all reference vehicles in the simulation are equipped with a variation of the application modules.

ad hoc VehicleMainModule + VehicleAdhocModule

cellular VehicleMainModule + VehicleCellModule

hybrid VehicleMainModule + VehicleAdhocModule + VehicleCellModule

The Internet based traffic server is equipped in all scenarios with the ServerModule. In the given assumption, however, it is only able to receive and send messages over the cellular network. Hence, the traffic server could only interact with the vehicles with the VehicleCellModule.

IEEE 802.11p Parameter	**Value**
Carrier Frequency	5.9 GHz
Bitrate	6 Mbit/s
TxPower	50 mW
RxSensitivity	-85 dBm
ThermalNoise	-94 dBm
AntennaGains	0 dBm
Cellular Parameter	**Value**
Region UL Capacity	28.0 MBit/s
Region DL Capacity	42.2 MBit/s
Region DelayModel	GammaSpeedDelay
Region UL/DL minDelay	40 ms
Region UL/DL expDelay	150 ms
Network UL/DL Capacity	100 MBit/s
Network DelayModel	SimpleRandomDelay
Network UL/DL minDelay	10 ms
Network UL/DL maxDelay	30 ms
Network UL/DL delaySteps	3

Table 5.2: Simulation parameters for the communication properties

5.3 Simulation Results

In the following, the safety capabilities of the different communication approaches are analyzed with the help of the presented metric of the safe time ratio (STR). Afterwards, the mean squared error (MSE) is used to measure the quality of the general information dissemination over a longer range in the whole scenario. Most traffic efficiency applications usually base on such a dissemination principle.

5.3.1 Safety Metric

The results for the STR are presented in the Figures 5.2, 5.3 and 5.4. The graphs show the STR in dependency on the real-time requirement τ. The variation of the graphs depends on the relevance area time (t_R). In this evaluation, to the linear distance between the two vehicles defines the relevance area. However, the definition could also incorporate further parameters as a converging trajectory, the same road or even lane etc. to limit the area to a more restricted set of relevant vehicles (e.g. eliminate vehicles in the opposite direction on a motorway). The linear distance, nonetheless, includes the most demanding properties. The selected distances address the safety zones of Figure 2.1 and their according use cases. The close distances of 28, 55, 83 m would account for near field use cases in the Maneuver zone, the medium distance of 139 m in the Warning zone, and higher

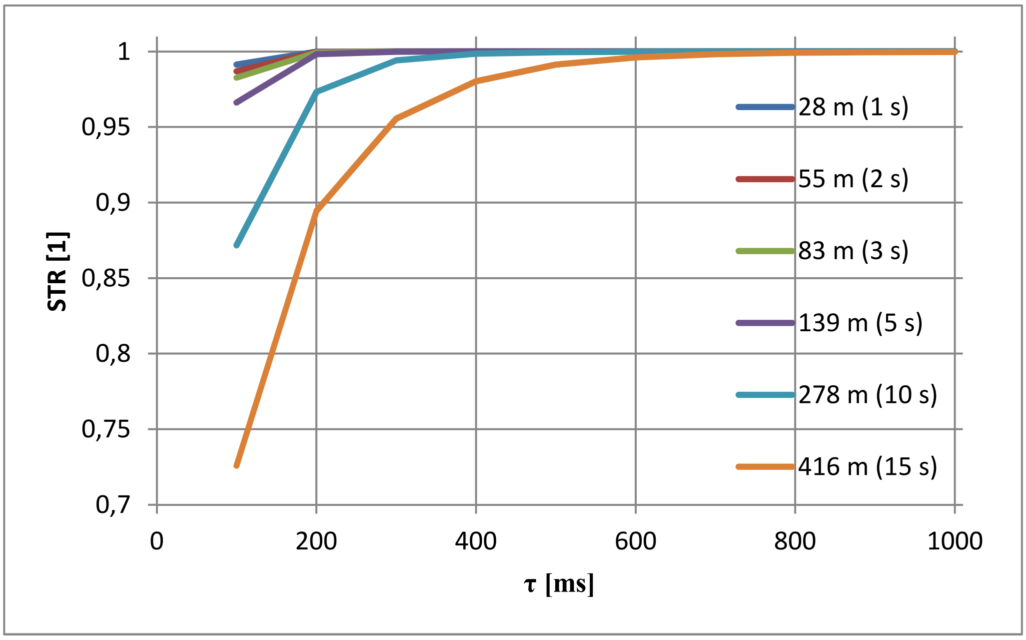


Figure 5.2: Results for safety metric STR for the ad hoc variation

distances of 278 and 416 m in the Awareness zone. For instance, the Intersection Collision Warning would operate in close distances in the Maneuver zone, the Electronic Brake Light Warning in the medium area in the Warning zone and use cases with a slightly longer horizon, such as the Approaching Emergency Vehicle Warning would operate in the Awareness zone. Use cases in the Information zone would be better evaluated with the MSE as discussed later.

The results in Figure 5.2 show for the ad hoc case in the near field relevance areas (28, 55, 83 m) that the STR already starts with sufficiently high values of 98 to 99 % even for the most demanding τ of 100 ms. It quickly converges towards 100 % with a more relaxed τ. This is a result from the good communication properties of the direct IEEE 802.11p broadcasting with very short delays in the order of low ms and the low packet losses in close distances. The performance decreases for increasing distances of the relevance area. Actually, the highest presented distance of 416 m should be still well limits of the communication range for the given IEEE 802.11p configuration (with the parameters of transmission power, receiver sensitivity etc. see Table 5.2). However, the results reveal the known PHY Layer issues of increased packet loss due fading, shadowing and also MAC layer coordination issues as collisions due to the Hidden Terminal Problem. Even in this moderate scenario, burst errors of spans longer than 7 consecutive CAMs result in convergence of the STR graph towards 100 % not until a τ of 700 ms. For higher relevance areas, the figures would turn out even more critical.

For the cellular case in Figure 5.3, all STR graphs show an equal trend, which is independent from the relevance distance. Actually, this reflects the expectation

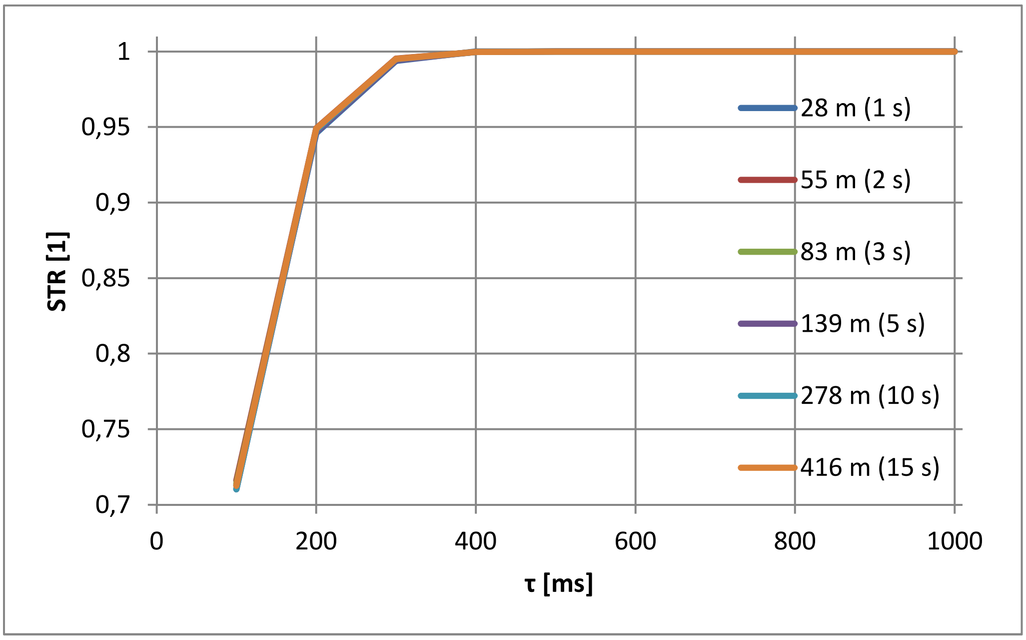


Figure 5.3: Results for safety metric STR for the cellular variation

value of the underlying models of the regions with sufficient capacities to deliver all transmitted CAMs with the given delay distribution. One can see that there is a certain probability that messages are received out-of-order when particular messages e.g. take a longer way through the network with a higher latency. As the considered safety use cases mainly require the freshest updates of the CAMs only, older messages are dropped and neglected for the CCP and STR evaluation. That means even when the data throughput of cellular networks is acceptable, the delay limits the performance the use cases with real-time requirements less than 400 ms. This could be critical especially for use cases in the near relevance area of 28 or 55 m, where ad hoc communication shows its advantages of short latencies. When the future 5th generation of cellular networks can reduce latencies to the required scale, they could be a serious alternative for safety use cases.

For now, the hybrid approach to send CAMs via ad hoc and cellular networks could be used as a migration path. The hybrid approach shows a similar trend as the cellular approach for the highest presented relevance distance of 416 m to support use cases with a τ of 400 ms fully with 100 %. It even starts at slightly higher figures for the most demanding τ of 100 ms as the reception of short-delay ad hoc messages improves the performance. With decreasing distance for the relevance area, the ad hoc transmission appears to be dominating. Due to this, the hybrid approach delivers the equal result compared to the ad hoc approach.

Hence, it could be stated that the hybrid approach incorporates the advantages of short latencies the ad hoc approach in the near field and also supports higher distances as the cellular approach.

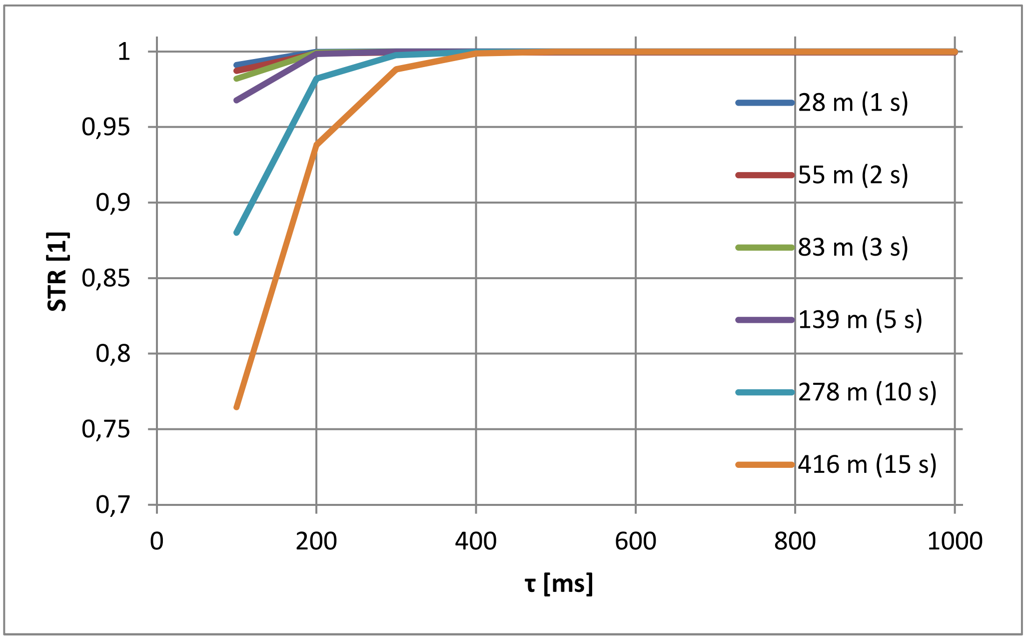


Figure 5.4: Results for safety metric STR for the hybrid variation

5.3.2 Efficiency Metric

Figure 5.5 depicts the development of the normalized MSE on the vehicles during the simulation time. It includes three graphs for the three different communication approaches (ad hoc - blue, cellular - green, hybrid - red). The very early and final phases of the simulation, when many vehicles still have to enter or, respectively, already left the simulation, are cut away. However, it is still worth to examine the transition phases which would depict situations where the vehicles and thus the traffic information are not well distributed, but concentrated locally. Such situations may for instance appear temporarily in low traffic periods or in the early stage of system introduction when the penetration rate is generally low.

The trend of all graphs shows that the MSE generally decreases over the simulation time. It very slightly increases in the final phase when the first vehicles leave the simulation.

One can see that the ad hoc approach despite the short possible communication range even reaches similar figures for later simulation time compared to the other approaches. The applied information handling algorithm, which bases on the LDM, actually implements a typical store-and-forward semantic. This approach collects information and carries them with the movement of the vehicle to later retransmit the summarized information. This is a very efficient method to increase the dissemination area for more delay tolerant information. However, the blue graph for ad hoc communication takes a longer time span to decrease as the vehicles have to drive a certain time to meet and exchange the information they

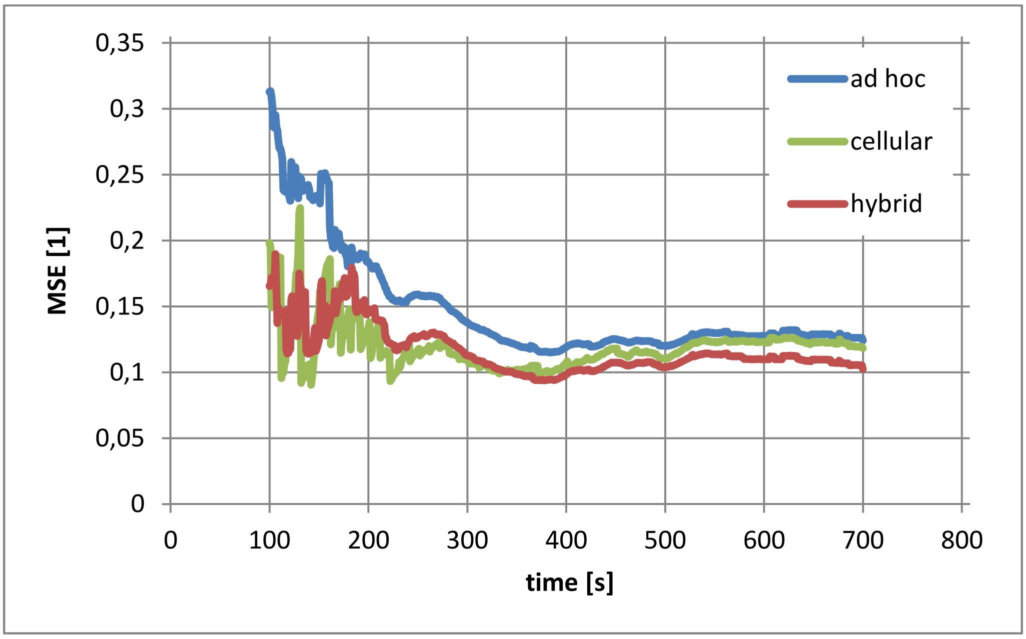


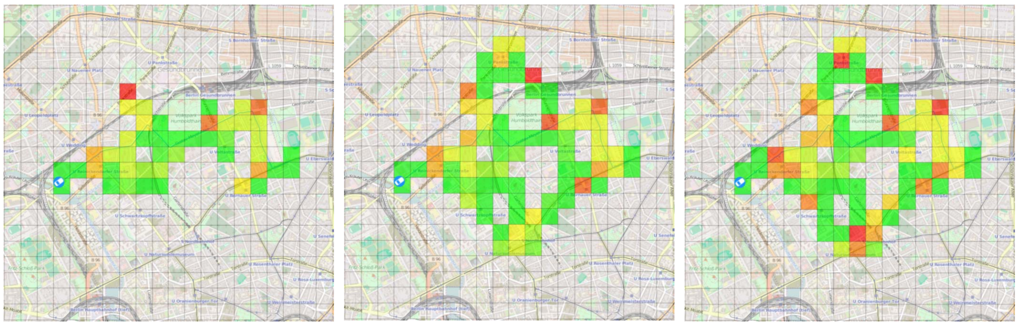
Figure 5.5: Results for efficiency metric MSE for different equipment settings

have collected on their way.

The visualization of the perceived speed information in the LDM Grid for one representative vehicle in Figure 5.6 explains this behavior. The three images display the collected speed information, matched to a LDM grid in the colors from red for low, over yellow for medium, to green for high speeds. Empty pixels in the grid stand for missing information. Actually, the available data and hence the pixels colors change over the simulation time but this visualization focuses on a fixed time at the end of the vehicles route. The reference data grid (c) on the right side depicts the vehicle movements and includes the true information. Empty pixels in the reference data imply that the vehicles did not route through the whole environment. The grid (a) on the left side displays the data, which can be received from the neighbors via CAMs. Only with CAMs, the vehicle obviously misses particular information and has only few filled pixels. The CAM plus FCD messages grid (b) in the middle already receives messages from all pixels. However, for individual pixels, the perceived information vary from the reference data thus resulting in a certain MSE.

Back to Figure 5.5, the graphs for the cellular and hybrid approaches already start a fairly lower MSE values in the beginning of the simulation, in comparison with the ad hoc approach. This is due to the fact that the Traffic Server can quickly mirror the perceived traffic information back to the equipped vehicles. In the later simulation time the hybrid approach slightly outperforms the cellular approach.

In summary, it could be stated that the cellular approach in this time already



(a) CAM Data (b) CAM + FCDmsg Data (c) Reference Data

Figure 5.6: Perceived speed information in the LDM Grid for one vehicle, underlying visualization based on map from OpenStreetMap [Ope15]

delivers sufficient results for information dissemination. The hybrid approach with additional messages over ad hoc communication may still improve the redundancy. Nonetheless, the presented information handling application is still very simple and could be still improved with more advanced techniques for data aggregation e.g. from the field of machine learning. However, this was out of scope of the presented evaluation.

5.4 Summary of Simulation Analysis

Ad hoc networks based on IEEE 802.11p enable a decentralized information exchange among vehicles and among vehicles and infrastructure units. The implemented V2X applications can benefit from the short transmission latencies, which result from the direct broadcast characteristics of this approach. Since the limited communication range and the lack of deterministic quality of service poses a challenge for the scalability of ad hoc networks, some new approaches try to overcome these drawbacks by using cellular networks for the information exchange. However, although cellular networks enable a nearly unlimited communication range, the architecture of these networks can involve a delay in information transmission which might violate the strong requirements of many safety applications. To benefit from the advantages and reduce the drawbacks of both networks types, an intelligent combination of vehicular ad hoc networks and cellular networks could help. Detailed investigations are needed to evaluate in which cases pure ad hoc networks, pure cellular networks, or a combination of both would be the best. The simulation study, presented in this work, gives an example to show how the research in this area can be addressed.

Chapter 6

Conclusion

The final chapter of this thesis recapitulates the presented work in a brief way and gives an outlook for future work and improvements which are based on the gathered experiences.

6.1 Summary

Today, the many advantages of V2X communication use cases on future intelligent transportation systems are well-known. However, it is still unclear which underlying communication technologies will exhibit the potential to enable the implemented applications. There are mainly the two possibilities of wireless ad hoc network with decentralized communication as well as cellular networks with deployed infrastructure in the back end. This thesis investigates on heterogeneous solutions where both communication stacks will exist. Accordingly, it is possible that the two communication systems complement each other in certain scenarios in a meaningful way in order to fill respective technological gaps.

In principle, the different applications exhibit different characteristics and requirements towards the communication technology. For instance, traffic safety and efficiency applications rely on the information exchange between many end points, while personal comfort applications are typically limited to two points, the client and the server. Tolerable communication latencies are more strict for safety than for efficiency applications, and so on. For these reasons, this thesis started with a classification of conditions in several dimensions for all envisioned applications for day one of the introduction and current application trends. Additionally, it introduced the Consecutive CAM Period (CCP) as an awareness metric to address especially the comparison of the mobility-related applications, as they might have the highest benefit for future transport.

The main part of this thesis focused on enabling the investigation and comparison of the heterogeneous ad hoc and cellular communication approach by simulation. Therefore, the V2X Simulation Runtime Infrastructure (VSimRTI) was improved and extended in different ways. For ad hoc networks, it was, consistent with other research, identified that especially the modeling of the radio signal propagation has a major impact on the communication properties. Common simulation models do not take into account all aspects of the highly mobile vehicular environments. Notable examples are characteristics as the Doppler Effect, which arises due to high vehicular speeds or the time-varying shadowing effects, which appear especially in urban settings due to the buildings. Consequently, this thesis presented two approaches for improvements of current propagation models. The deterministic simulation of site-specific communication models accounted for buildings as shadowing objects. The advanced statistical modeling, based on a measurement campaign, considered all fading and shadowing effects for different vehicular movement constellations and speeds in different urban and rural environments. As a result, certain applications were strongly influenced by the communication capabilities. The other part of heterogeneous networks concerns cellular systems. Again, the wireless characteristics are of high importance. Additionally, these systems include a significant portion in the wired backbone network. The modeling of each individual node of the whole cellular system would reach its limits in larger scale vehicular scenarios. On that account, this thesis introduced a new simulator VSimRTI_Cell as solution to cover all important aspects of the cellular networks as the radio access and the core network and various advanced features, e.g. (e)MBMS to enable cell-broadcast approaches. VSimRTI_Cell regards for the most important parameters such as communication latencies, packet losses and cell capacities. It enables the simulation of communication in local to wide-area networks with different coverage properties.

The final part of this thesis connected the preliminary working packages in a simulation study. This study analyzed reference applications for the classes of traffic safety and efficiency with the use of the proposed evaluation metrics. The applications were not investigated in isolated scenarios, but simulated together in one heterogeneous scenario to explore the interdependencies of applications and ad hoc and cellular communication technologies. In general, the direct ad hoc communication could deliver lower latencies for safety critical applications in the close range. For delay-tolerant applications, the applications used a model of a Local Dynamic Map (LDM) for location-based data storage as the pivotal point of information handling. The LDM actually enables a store-carry-forward pattern to facilitate information exchange. Hence, the LDM increased the information range substantially also for the case of decentralized ad hoc communication. However, it partially carried outdated data for distant locations. The cellular path to a central server complemented this drawback. Finally, it could be stated that the equipment of vehicles with both stacks is also more robust as it also works in areas without cellular coverage. Yet, these advantages may come at the price of both physical hardware for the ETSI ITS and e.g. the LTE modems.

6.2 Outlook

Certainly, this thesis could only cover a limited area of research. During the time of working for this thesis, the Local Dynamic Map was discovered as particularly important for data handling, enabling hybrid information exchange and facilitate V2X applications. Moreover, the advent of new concepts of LTE-V2X to enable direct communication is a very interesting a relevant building block for the system design of V2X communication.

The LDM is not an entirely new concept. The LDM facility to store location-based information is already specified in the ETSI ITS standard. In the meanwhile, there are different architectures for the LDM with slightly varying details, from a simple white board pattern to a layered LDM with layers parameters of different time dynamics. The LDM needs highly efficient algorithms for data fusion and aggregation from different input data, and extrapolation mechanisms to serve data for consuming module with different time scales. For autonomous driving applications, the data amount will definitely increase compared to driver assistant applications. Therefore, filtering mechanisms could reduce the handled data amount. For instance, an electronic horizon would limit the data topologically to the predicted route of the vehicle. Data synchronization with Cloud or mobile edge servers would complete the concepts of a distributed system.

LTE-V2X was published in 3GPP Release 14 in June 2017, just slightly before the thesis completion. LTE-V2X is based on the specifications for LTE-D2D, which adds a sidelink for direct communication between UEs to the typical up- and downlink from UEs to eNodeB. For medium access control, LTE-V2X relies on Semi-persistent scheduling (SPS), a MAC approach that aims for periodic transmission attempts, similar to the alternative access approaches of STDMA and MS-ALOHA. LTE-V2X supports different modes of operation. Mode 4 specifies a distributed resource scheduling. It works without subscription to an eNodeB, thus also in out-of-coverage scenarios. Mode 3 improves the spectral efficiency. In this mode, the transmission is still direct, e.g. from vehicle to vehicle, but the media access is managed centrally via the eNodeB, to which the vehicles are subscribed. Hence, mode 3 requires a connection with an MNO, also generates corresponding efforts for the MNOs and would not be for free. Preliminary simulation studies see slight advantages compared to the IEEE 802.11p standardized DCF or EDCA MAC. However, these conclusions might result from the scenario assumptions of pure periodic traffic. It would be very interesting to reproduce such simulations with VSimRTI.

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