1 Introduction

Active safety in road traffic has become an important topic in the automotive industry. Enabling vehicles to directly communicate with each other opens a huge field of new functionalities. Most promising are the active accident prevention and mitigation which is expected to significantly reduce fatalities and injuries in road traffic. Besides safety, infotainment and traffic applications can be realized based on intervehicle communication.

Intervehicle communication, also referred to as Vehicular Ad-Hoc Networks (VANETs) is enabled by wireless communication which allows vehicles to exchange each other's status. Moreover, vehicles can warn each other immediately of safety-critical events on the road and imminent dangers. Hence, vehicles establish awareness of each other in a cooperative way. As an extension to the driver's own perception, this is also called electronic horizon.

This information exchange has to happen within few milliseconds so that each vehicle can accurately determine the location, heading and speed of the surrounding vehicles. Moreover, with the reliable exchange of status updates, each vehicle can determine if there is any imminent danger of which the driver has to be informed of. Moreover, in case of pre-crash applications, other active safety systems like airbags can be appropriately prepared for an impact.

Especially for the safety-critical applications like forward collision warning or intersection collision warning, low delay communication is essential. Cellular communication with its requirements for base station presence, carrier contract and complex connection setup procedures is not suitable for the safety-critical applications. Thus, besides cellular communication for infotainment and delay-tolerant applications, ad-hoc communication according to IEEE 802.11 is intended to be employed for intervehicle communication.

Currently ongoing efforts in (telecommunication) standardization bodies like the Institute of Electrical and Electronics Engineers (IEEE), International Organization for Standardization (ISO), International Telecommunication Union (ITU), European Telecommunications Standards Institute (ETSI), European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC), and the Association of Radio Industries and Businesses (ARIB) jointly work on a harmonized solution for intervehicle communication worldwide. All of them are based on IEEE 802.11p, the amendment for VANETs, which defines Physical (PHY) and Medium Access Control (MAC) layer. Different variations are under discussion which focus more or less on the integration of vehicle-to-infrastructure communication and geographically-scoped routing. Most regions in the world have ratified that the intervehicle communication should take place in the 5.9 GHz band with channels of 10 MHz bandwidth. One Control Channel (CC) is mandatory to be used for safety-critical information. Depending on the allocated total bandwidth, various Service Channels (SCs) may be used for less-safety critical information. Note that in the remainder of this thesis, the terminologies and regulations as specified by ETSI are applied.

In all regions, the common communication pattern is the single-hop periodic broadcast of so-called Cooperative Awareness Messages (CAMs) on the CC. These status messages are also referred to as (application-layer) beacons, heartbeats, or Basic Safety Messages (BSMs). Each CAM contains the originating vehicle's ID, its location, timestamp, and heading. Usually, after receiving a CAM, each vehicle temporarily stores it in the so-called neighbor table in order to establish the "map" of surrounding vehicles. Besides the CAM, two other message types are primarily foreseen by ETSI. In case of detection of critical events, vehicles immediately send so-called Decentralized Environmental Notification Messages (DENMs). For example, if a vehicle performs emergency braking, a DENM is generated immediately when the vehicle detects that the driver brakes abnormally strong. Another message type is the Service Announcement Message (SAM). Vehicles may be informed of special communication services like detailed information on the intersection that is currently approached. These three mentioned message types are usually not forwarded or routed. Under discussion is the so-called Geocast [72] of messages to extend the physical transmission range. This type of communication is out of scope of this thesis since it induces significant delays and thus may not be applied by active safety applications with strict timing constraints.

As the intervehicle communication has many interdependencies with road traffic, many characteristics and limitations stem from road traffic engineering. That is, the various road traffic conditions such as high relative movements and high densities of vehicles in combination with the challenging conditions of wireless outdoor communication make this kind of communication unique. Moreover, as CAMs have to be sent with a high rate to ensure the availability of up-to-date information, the unique problem of high channel load and the resulting performance degradation is of great interest. Effects like packet collisions, significantly higher medium access delays as well as message queue drops are known to reduce the effectiveness of active safety applications in intervehicle communication.

The traditional approach to radio resource management as applied for classic wireless Local Area Networks (LANs) usually tries to avoid an overload of the Access Point (AP) as well as mitigating the co-channel interference [50]. A cross-layer management plane performs this radio resource management. Since the AP is a central controlling element, it can order single Stations (STAs) to reduce the transmit power. In case of multiple controlled APs, STAs can be re-associated to other APs to balance the load. Moreover, STAs can be ordered to apply higher modulation rates in order to reduce the channel occupancy.

However, VANETs have significantly different characteristics so that the aforementioned approaches cannot be applied. Therefore, the specific problem for efficient radio resource management in intervehicle communication is stated in the following section.

1.1 Problem Statement and Approach

The communication in intervehicle communication for the purpose of active safety has to be as reliable as possible. It is already clear that (ad-hoc) wireless communication cannot guarantee 100% reliability and thus availability. Unpredictable circumstances like obstructions due to buildings can interrupt the communication. Heavy usage of the medium and external influences lead to interference and hence a lower communication quality. Furthermore, the rapidly changing network topology poses two specific problems to the communication: First, parts of the topology may be still unknown as there may be vehicles that just have entered the communication range but have not sent any information about their presence. Second, vehicle densities may change from very high to very low and vice versa. On the one hand, this may overload the communication channel in case of high density. During the transition to very low density, the system has to be prevented from transmitter-blocking, due to a too sensitive carrier sensing.

Especially the latter issue makes the design of mitigation techniques quite difficult. In classic wireless communication, a central coordinator (e.g. an Access Point (AP) or a Base Station (BS)) can observe the links to all connected stations. Based on link statistics, the coordinator can provide STAs with information on how to adjust the transceiver. Moreover, the four-way handshake allows to detect transmission errors and appropriate actions like the increase of the contention window can be done as a means to reduce medium access collisions. However in VANETs, the approach of a central coordinator is not feasible. On the one hand, additional message overhead and delays are not acceptable because of delay sensitivity of the active safety applications. Furthermore, the highly dynamic network topology would also demand a continuous re-organization of the roles of the vehicles. Thus, decentralized multiple access schemes have to be applied where all involved vehicles have the same privileges.

More specifically, the increasing vehicle densities pose a problem to multiple access techniques. The distributed medium access in terms of Carrier Sense Multiple Access (CSMA)/Collision Avoidance (CA) inevitably results in medium access collisions. Even worse, the wireless medium may get fully loaded such that no additional transmission is possible. The communication channel is getting locally congested. In the end, this results in undesirable information loss, especially in situations where a large number of vehicles accesses the communication channel with high frequency. In these situations, communication and thus cooperative awareness suffer from increased packet loss.

The challenge in this thesis is to develop a suitable dynamic adaptation of each vehicle's communication system to mitigate the aforementioned performance degradation. Adapting the whole intervehicle communication system comprises a multitude of parameters and options. Optimizing them in a target-oriented way, with the background of active safety goals, road traffic characteristics and wireless communication poses the following research question:

Which parameters on which protocol layers allow for an improved communication so that dangerous situations on the road can be detected more reliably?

These parameters span from transceiver-related parameters like transmit power, modulation rate, carrier sensing configuration up to application-related parameters like message generation rate and message repetition strategies. As the strict protocol layering structure should be maintained, a merging of all protocol layers and thus a multi-parameter optimization cannot be performed. Moreover, it would not be appropriate since the magnitude of solutions may lead to unpredictable behavior of the communication system, which has to be prevented by all means. Instead, it is assumed and to be proven that mechanisms acting at single layers should basically adapt the layer-specific parameters with the available knowledge of the respective layer, i.e. in an isolated-adaptive manner. The approach of the isolated or local adaptation has been a common approach in routing algorithms [113]. In a distributed way, nodes take decisions based on knowledge they gathered independently without any communication between each other. Besides avoiding message overhead, this has the advantage that the behavior of the mechanism(s) can be easily traced and potential misbehavior can be predicted already in the design phase, based on the reduced complexity of the approach.

Beyond the single-layer mechanisms, a cross-layer coordination entity should gather the locally available data on characterizing the current road traffic situation, application requirements and the current channel condition. In a bottom-up manner, it should be based on single layer approaches and execute pre-defined actions based on a well-defined set of system states. The hypothesis to proven can thus be formulated as a second research question:

How can these parameters be adapted in a coordinated manner in order to significantly improve the communication performance?

As explained before, these significant improvements can be expected only when there is a performance degradation, for instance because of interference. This interference is likely to occur because of high load on wireless channel. Therefore, the problem of unmanaged intervehicle communication will become significant mainly when there is a certain penetration rate, deployed on the road. A potentially high channel load will not occur during the market introduction phase, to be planned for the year 2015. At higher penetration rates, high load/density will occur and even regularly for certain drivers that pass certain high density areas. However, most challenging are only those situations where there is high movement and high density in parallel which is usually not the case as such situations mostly result in traffic break downs and hence traffic jams. To understand these considerations better, a review of road traffic research and engineering will be performed to derive scenarios that reflect the aforementioned challenging conditions and conduct performance evaluations.

1.2 Contributions of this Thesis

Based on the problem as stated previously, a qualitative comparison of existing performance analyses and evaluations as well as suitable countermeasures has been performed. For this comparison, it is important to understand the specific requirements for the communication system. Thus, an extensive set of requirements has been defined for both, the problem analysis and appropriate resource management systems. As a result of the survey, the state of the art does not address problem appropriately, nor has the problem and resulting opportunities been understood sufficiently. Therefore, the problem analysis in this thesis provides the following contributions:

- The different cases and origins of packet loss have not been distinguished sufficiently. To develop suitable countermeasures, it is important to understand which origin of packet loss is targeted and which side-effects may occur. Thus, in this thesis, even extreme conditions of channel load are investigated.
- Particularly, the carrier sensing has so far not been analyzed in the context of VANETs. The problem analysis in this thesis investigates the different options and identifies the solution space, in terms of reliability versus medium access delay.
- By a real-world experiment, it has been found that the classic hidden station problem can become even worse when considering different vehicle heights which have different shadowing characteristics. These vehicles and the vehicles close to them are subject to significant packet loss.

Compared to the existing resource management concepts there is no approach that addresses these specific communication performance issues in parallel with the scenario-specific application requirements. Thus, three single-layer approaches have been developed, which adapt certain parameters or provide additional functionality to improve the reliability of cooperative awareness.

- A control of the locally offered load is conducted by Situation-Adaptive CAM Rate Adaptation (SCR). It considers the current road traffic situation as well as the own vehicle status to adapt the CAM rate.
- A selective forwarding of CAMs as realized by Selective CAM Forwarding (SCF) can mitigate single packet loss. This encounters the problem of shadowing as well as collisions due to simultaneous transmission and hidden stations.
- Under high load, the adaptation of the carrier sensing by CCA Threshold Adaptation (CTA) can resolve the blocking of the transmitter. Moreover, unfairness in the carrier sensing can be compensated by CTA.

These approaches act in an isolated way, independently of each other. Their complexity is relative low, so that they can easily be implemented via their lightweight design. Furthermore, they are compliant to the European standardization and have even partially become part of one of the standards, i.e. ETSI TS 102 687 [36].

In order to use the individual approaches in an integrated manner, coordination actions are required. Therefore, and to further increase the benefit of a joint operation, an cross-layer coordination called VANET Resource Management (VRM) is developed in this thesis. Thus, VRM has the following characteristics:

- In an isolated-adaptive manner, VRM coordinates the single-layer mechanisms so that they can run efficiently together.
- By a bottom-up design, VRM classifies the current road traffic situation and the channel condition. Thus, it triggers coordinating actions for the single-layer mechanisms to limit or extend their engagement based on cross-layer knowledge.

- VRM has a very limited set of states to keep it lightweight and traceable.
- Input metrics for VRM have been reviewed and refined such that the resolution and accuracy are increased to determine the current state of road traffic and channel condition in consideration with the requirements of the currently engaged active safety applications.

Extensive simulation studies have shown that the situation-adaptive coordination of the communication system by VRM can significantly improve the cooperative awareness and the corresponding position accuracy.

1.3 Structure of this Thesis

As a basis for specific problem analyses, chapter 2 provides the background on wireless communication in general and the already standardized protocol architecture for ITS by ETSI in particular. Important aspects of wireless communication like shadowing and interference are explained in order to build upon this knowledge later on. Characteristics of road traffic, major differences between urban, rural and highway traffic are explained and compared. Then, simulation of wireless communication and road traffic is explained as well as the simulation environment that has been developed for this thesis.

The requirements for efficient resource management in VANETs open up chapter 3. These requirements motivate for certain research and development steps. Existing performance evaluations and analysis are compared which lack of certain VANET-specific characteristics that demand for a specific problem analysis. The most relevant and/or commonly cited existing approaches for radio resource management are compared, which also motivate for significant improvements.

Chapter 4 covers the specific analysis of overloaded VANETs. Moreover, based on the road traffic characteristics explained in chapter 2, reference road traffic scenarios are established, which are used throughout the thesis for discussions and evaluations. Results from simulation studies and real-world measurements quantify and classify the problems occurring during or in the transition to the overload. The most significant problems are highlighted.

In chapter 5, the cross-layer coordination approach called VANET Resource Management (VRM) is developed, which addresses the most significant problems. To introduce VRM, the architectural integration into the ETSI protocol architecture is explained first. Then, the individual single-parameter mechanisms are introduced, namely Situation-Adaptive CAM Rate Adaptation (SCR), Selective CAM Forwarding (SCF), and CCA Threshold Adaptation (CTA). After that, VRM is explained in more detail and sample configurations are proposed.

To evaluate the performance of VRM, chapter 6 initially states the research questions and summarizes the newly introduced evaluation metrics. Afterwards, the individual mechanisms are evaluated in various scenarios and their respective shortcomings are summarized. Finally, a performance evaluation of the complete VRM investigates which individual shortcoming can be compensated and the overall improvement of the communication performance is highlighted.

Finally, conclusions are drawn in chapter 7 summarizing the specific problem analysis as well as the design and evaluation of VRM. The outlook identifies aspects for improvements of VRM which is subject to future work.

2 Background

Intervehicle communication connects various fields of research. This chapter will therefore contain basic knowledge on wireless communication which forms the basis for the more specialized intervehicle communication. The structure of this explanation follows the common Open Systems Interconnection (OSI) model, established by the International Organization for Standardization (ISO) in [2].

The general performance limitations of wireless communication already imply requirements from the lower layers of the OSI/ISO reference model. Active safety applications at the top of the reference model imply strict requirements on the freshness and accuracy of the provided information. In-between, different abstraction layers have to mediate these requirements.

The necessary background for the requirements at the lowest and highest layer is explained in this chapter, starting with the basic knowledge on wireless communication. Then, the current state of the foreseen ETSI protocol stack architecture is reviewed, ending up with the application layer, including applications to save motorists' life. To understand the requirements there, a review of road traffic characteristics and dangers in road traffic is given. To evaluate the approaches presented later in this thesis, simulation tools and prototypes for intervehicle communication are presented at the end of this chapter.

For supplementary literature on signal propagation and antenna designs, the reader is referred to the book of Godara in [43] and the book of Rappaport in [86]. A more extensive overview on intervehicle communication can be found in the book of Hartenstein and Laberteaux in [47].

2.1 Wireless Communication

The communication between two parties is always done over a logical principle called "channel". Shannon defines it in his article [111] as follows

"The channel is merely the medium used to transmit the signal from transmitter to receiver. It may be a pair of wires, a coaxial cable, a band of radio frequencies, a beam of light, etc."

Several limitations on the performance arise due to the physical environment as well as other communication nearby, limiting the communication range and increasing

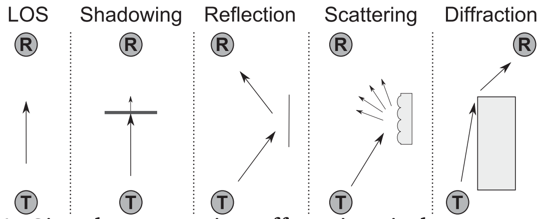

Figure 2.1: Signal propagation effects in wireless communication.

the error rates. The fact that wireless communication uses the air as shared propagation medium imposes these limitations which do not arise in wired communication. The advantage of wired communication is that the channel is well-isolated and the attenuation is very low in a medium like copper [18] or a fiber optical medium.

The remainder of this section summarizes the challenges of a wireless medium, i.e. the signal propagation of radio waves. Key aspects therefore are communication range and error rate (of bits or packets). From a single transmitter's point of view, signal attenuation is the most significant limiting factor for the communication range. It can be divided into a small and large scale part, i.e. fading and path loss. Small-scale fading, e.g. Doppler spread will be neglected here as the focus is mainly on the total signal power which results in interference in far distances. Moreover, Doppler shifts can be assumed to be compensated by advanced receiver technologies that allow better equalizing and improved synchronization techniques, as described by Mittag et al. in [77]. For further details on the impact of Doppler spread the reader may also refer to the work of Zhang et al. in [131].

Large-scale fading will be described in the first part of this section. The second part covers the topic of external influences, which reduce the communication range: Interference and Noise. The Signal-to-Noise Ratio (SNR) is used to express the strength of a focused signal compared to the noise, whereas the Signal-to-Interference-Noise Ratio (SINR) accumulates the noise and the sum of all interfering signals in relation to the focused signal.

The development of models for radio signal propagation is typically done using statistical values from particular regions or even cities. Practical measurements made for a particular communication system in the respective environment are taken to build up such a statistical model [86]. Path loss models compute the signal attenuation or received signal strength for a given distance between transmitter and receiver. Besides signal attenuation due to air propagation there are other important attenuation influences (depicted in figure 2.1):

- *Shadowing:* Particular objects reflect the wave into the opposite direction or strongly attenuate the signal so that behind these object only a weak signal remains.
- *Reflection:* The electromagnetic wave is reflected by a large surface with a comparably higher dimension than the wavelength.
- *Scattering:* In contrast to reflection where the surface must be relatively large, scattering occurs at small dimension surfaces compared to the wavelength. Rough surfaces like plants or trees scatter the wave to multiple directions.
- *Diffraction:* The wave is bent behind a sharp edge of an object. Thus, the wave is able to propagate beyond shadowing objects.

In VANETs, reflection and shadowing are more significant effects than diffraction. A commonly huge surface for reflection effects is the surface of the Earth. Regarding shadowing, large vehicles like trucks strongly contribute to signal attenuation. Diffraction mitigates the impact of shadowing, allowing signals being bend around a corner. Scattering additionally decreases the received signal power since it is spread into different directions.

Following, common models for these effects are explained which estimate the average received signal strength. Note that sophisticated models like ray tracing which accurately track the path of each beam are not considered further since they are computationally highly expensive. The reader is kindly referred to an interesting discussion on ray tracing in outdoor urban wireless networks, done by Moser et al. in [83] and Schumacher et al. in [105].

2.1.1 Large-scale Signal Attenuation: Path Loss

A common (non-statistical) model that allows to compute the received signal strength in Line of Sight (LOS) is given by the simple transmission formula established by H. T. Friis [37] in 1946. It only considers the signal attenuation over the air and neglects Non-Line of Sight (NLOS) components. Assuming an omni directional antenna, the signal power is projected to an area, the surface of a sphere. Hence, it attenuates quadratically with the distance to the transmitter or, more specifically to the antenna. The equation for the received power P_r at distance d is denoted as follows:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{2.1}$$

with P_t the output power of the transmitter, the antenna gains at transmitter and receiver, i.e. G_t and G_r , the wavelength λ and the system loss L which is not related to propagation. As seen in the above equation, the received power P_r depends mainly on the distance d of Transmitter-Receiver (T-R). This model has been formerly used for satellite communication and microwave radio links but can be also used for other wireless communication appliances [86].

When considering the effect of reflections, it becomes obvious that in ground-to-ground communication there is always one large surfaces present: Earth's surface. Moreover, in urban areas large surfaces are provided by buildings and other facilities that additionally reflect radio waves. The effect of the reflection from the ground surface is typically modeled using the Two-Ray Ground (TRG) model. Similar to Friis' simple transmission formula, the received signal power is computed but with a different path loss exponent and under consideration of different antenna heights:

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4}$$

with h_t and h_r being the antenna heights of transmitter and receiver over the ground. In the formula, the reflection from the surface of Earth is considered only.

Signal attenuation due to shadowing is commonly modeled using the Log-Normal Shadowing (LNS) model. As empirical data has shown that the path loss increases logarithmically with the distance, the log-distance path loss is commonly used [86]. Therefore, the consideration of a shadowing component makes this model suitable for VANETs. The respective formula determining the Received Signal Strength (RSS) in dBm is given by

$$P_r(d)\,[dBm] = P_t - PL(d)$$

with the path loss

$$PL(d)\,[dB] = \overline{PL}(d_0) + 10n\log\frac{d}{d_0} + X_\sigma$$

where $\overline{PL}(d_0)$ is an empirical value of the average path loss at the reference distance d_0 which is typically within 1 m. Free space propagation is assumed for this reference path loss. It can either be determined by the free space formula by Friis or through field measurements. The rest of the formula consists of the log-distance path loss model, and the zero-mean Gaussian distributed random variable X_σ with standard deviation σ (both in Decibel).

To account for stronger attenuation from a certain T-R distance on, a common approach is the dual-slope path loss extension with two distance-depended path loss coefficients [115]. Measurements in VANETs have shown reasonable values as $\rho_1 = 1.8$ and $\rho_2 = 2.8$ [62, 82] whereas ρ_2 is valid from an NLOS distance of 50 meters on. The deviation for the normal distribution is $\sigma = 3$. It is noteworthy that ρ_1 can be smaller than 2 which is due to constructive reflections of the buildings at the road-side. It can be expected that the path loss inside tunnels is even below 1 which is subject to ongoing research.

2.1.2 Signal to Interference and Noise Ratio

The signal quality and hence the ability to decode information from radio waves depends on the ratio between the focused signal and the sum of all present non-focused (and weaker) signals including the noise floor, which is called SINR. The stronger the signal, the better the signal quality and hence the lower the packet loss probability. The same consideration is valid for the interference, i.e. the weaker the interference, the better the signal quality. In the 5.9 GHz frequency band, external sources of noise are negligible as it is a dedicated spectrum. Usually, electrical devices operating at such frequencies like microwave ovens or microprocessors may cause interference, which is not the case at 5.9 GHz. Only the thermal noise and the interference by other transmissions need to be considered. Many external sources are negligible. Only few electric devices emit this high frequency. Industrial appliances do not operate there. The frequency band is protected outdoors by a licensed band by the Federal Communications Commission (FCC).

Thermal Noise In 5.9 GHz, atmospheric, cosmic or man-made sources do not significantly contribute to the noise level [43]. Only the noise in the receiver antenna has a noteworthy impact on the signal-to-noise ratio. It is often called *thermal noise* which is calculated using the respective equation as explained in [86]:

$$P_{Noise} = kT_0B \ .$$

The power of noise P_{Noise} depends on the bandwidth B and the temperature in Kelvin T_0. K is the Boltzmann constant with $K = 1.38 \times 10^{-23}$ Joule/Kelvin. The resulting noise floor for VANETs, using the commonly assumed ambient room temperature $T_0 = 300$ Kelvin (equivalent to 26.85 degrees Centigrade) [86] and a bandwidth $B = 10$ MHz is $-104\ dBm$.

Interference Interference has been known to be the key issue for the system performance in cellular networks for years [86]. It can be caused by stations transmitting in the same cell, in a neighboring cell or base stations in the same frequency band, also referred to as Co-Channel Interference (CCI). Inside these co-cells, the same carrier frequency is applied. Interference is usually mitigated by spatially separating the cells. Additionally, in cellular networks, interference is further tackled by a central managing entity, the so-called Base Station (BS) which organizes the transmissions of its connected mobile phones. Similar problems of interference arise in intervehicle communication. However, there will be no channel access coordination by a central instance due to the highly dynamic network topology.

For intervehicle communication, Orthogonal Frequency-Division Multiplexing (OFDM) schemes for signal modulation will be used (see section 2.2.2). As the name suggests, it follows multi-carrier approach where all carrier frequencies are orthogonal to each other. In such a setting, a high peak-to-average power ratio arises. Each sub-carrier may have a very high peak power. The result of such high power variations may lead to an out-of-band radiation. Power leakage and hence interference from neighboring bands into the currently used band is called Adjacent Channel Interference (ACI). For example, if there are two communication channels directly next to each other, the communication on each channel causes interference to the other channel due to out-of-band radiation of the transmitter [86]. Another cause is due to imperfect receiver filters where the receiver is not accurately tuned to the focused channel.

As long as the interferer is spatially separated sufficiently from the receiver, this interference may not lead to information loss. However, if the transmitter is far away from the receiver and hence has a high path loss, the receiver is more sensitive to a near interferer. This situation is commonly referred to as the Near-Far Effect. In other words, the interferer causes sufficient interference to the focused channel so that the SINR ratio becomes too low. Hence, the receiver is not able to decode information.

Especially in wireless ad hoc networks, the interference to unintended receivers significantly degrades the network capacity. Already simple ad hoc networks pose a problem to the estimation of the capacity. Information theory has therefore been focusing research on the 3-node relay channel problem as well as the 4-node interference channel, as described by Goldsmith et al. in [44] and Xue et al. in [125]. According to Goldsmith et al., determining the theoretical network capacity for these simple networks still remains open.

To summarize, two kinds of interference are common in intervehicle communication: CCI, ACI. These two have been described and will play in important role in the remainder of this thesis. Besides that there can be also Inter-Symbol Interference (ISI), and Inter-Carrier Interference (ICI) [86]. Both will not be considered further since they can be expected to be addressed by advanced receiver designs like the ICI self-cancellation approach by Zhao and Haggman in [132].

2.1.3 Multiple Access Techniques

As described before, wired communication has the advantage that only physically connected stations have to share the respective channel. In wireless communication, all stations in spatial proximity have to share the same channel. This sharing must be coordinated by a multiple access technique [86]. The following paragraphs briefly describe the available multiple access approaches from which the most appropriate one had been selected for intervehicle communication. Note that by the time of writing this thesis, discussions for different approaches were still ongoing (e.g. to improve spectral efficiency).

Originally, multiple channel access started with the desire to talk and listen at the same time in wireless telephone systems. This was the rise of duplexing techniques, either Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD). In FDD, two different frequencies have been used for sending and receiving, respectively. In TDD, the same frequency has been used, but half of the time for sending, the other half for receiving. The fractions are called time slots. In both cases, duplexing actually combines two simplex channels.

Multiple access techniques evolved by the strong need to support much more users while keeping duplexing. For example, a common combination is Frequency Division Multiple Access (FDMA) in combination with FDD. The users are separated by assigning different frequencies. However, it has to be ensured for duplexing that the frequency separation for sending and receiving is still acceptable. This is to save costs as for instance the same antenna can be used.

Besides FDMA, two other major techniques for multiple (user) access exist: Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). In TDMA, the users get assigned certain time slots where they can access the medium. This can be also combined with FDD and TDD. In CDMA, all users apply the same carrier frequency. Then, each user selects a pseudo-random codeword which has to be orthogonal to the others. When the codeword is correlated to the user signal, each receiving user can decorrelate using the desired codeword to receive only the wanted transmission. Common challenges of the latter technique are self-jamming and the near-far problem. If the codeword is not sufficiently orthogonal or if there is an undesired user close-by with high detected power, de-correlation and decoding of the information may not be possible. Hybrid approaches of the mentioned techniques also exist and are used for example in Global System for Mobile Communications (GSM). For further details, the reader may refer to the book of Rappaport [86].

Especially for low-latency wireless communication as desired in intervehicle communication, techniques of *Packet Radio* access are used. Basically, compared to the above techniques, the coordination overhead should be eliminated or reduced to a minimum. Transmissions are done in bursts of packets. Optionally, in case of simultaneous transmissions, the base station receiver replies ACKs and NACKs to indicate successful or failed bursts.

Prominent protocols are pure ALOHA and slotted ALOHA as well as Carrier Sense Multiple Access (CSMA). These protocols have different approaches to contend for medium access. Pure ALOHA is completely random access. Messages are transmitted as they arrive at the transmitter. Slotted ALOHA applies a lightweight scheduling, where users transmit within allotted slots or time intervals. This of course requires time synchronization among all participating stations. CSMA contains a slightly advanced scheduling approach where each transmitter listens to the channel before accessing i.e. the listen-before-talk principle.

ALOHA Due to their simplicity, pure ALOHA and slotted ALOHA can be easily analyzed regarding their performance in terms of delay and throughput. The delay does mainly occur because of retransmission due to collisions. For determining the trade-off between throughput and delay, constant packet lengths τ are assumed. The arrival rate of packets is assumed to be Poisson distributed with the mean arrival rate λ. Based on the normalized channel traffic R given as $R = \lambda\tau$, and the n packets being generated for a certain time interval, one can establish the probability of a collision as

$$Pr(n) = \frac{R^n e^{-R}}{n!}$$

From this equation, one can derive the respective equations to determine the throughput for pure and slotted ALOHA. For pure ALOHA, the vulnerable period of a packet collision is twice the packet length, i.e. 2τ. For slotted ALOHA, it is one packet length, i.e. τ. Thus, the derivative equations of $T_{pure} = Re^{-2R}$ and $T_{slot} = Re^{-R}$ leads to $T_{pure} = 0.1839$ and $T_{slot} = 0.3679$ Erlang.

Carrier Sense Multiple Access (CSMA) The previously described protocols do not listen to the channel before accessing it. Better performance to avoid collisions is expected, when sensing for a carrier before transmitting, which is the core idea of CSMA. Two important parameters exist that determine the time, how long to sense the medium: the detection delay and the propagation delay. The former is related to the receiver hardware. It describes the time (typically in microseconds) the hardware needs at minimum to measure and/or detect if the channel is idle or not. The propagation time denotes the time a signal needs to travel from the transmitter to the station that wants to transmit at the same time. These parameters have to be carefully chosen to support all involved types of receivers as well as the typical communication range.

Different variations of CSMA exist that are frequently used in communication systems. The *1-persistent CSMA* senses the channel till it becomes idle. Then, it immediately allows the transmission. In the *non-persistent CSMA*, the signaling via NACKs is introduced. Each potential transmitter backs off for a random timer after receiving a NACK. The *p-persistent CSMA* defines a probability p which determines if the packet is transmitted in the first available slot, or in the subsequent one with probability $1 - p$. This variation is close to the commonly used variation in wireless networks, as described in the next section. A more advanced variation which demands full duplex transceivers is CSMA with Collision Detection (CD). During the transmission, the channel is monitored for concurrent transmissions. After detecting such a collision, the transmission is immediately aborted. This principle is also known as *listen-while-talk*.

Out of these choices, a selection by IEEE has been made for the target multiple access scheme, which is an enhanced version of the p-persistent CSMA. Based on OFDM, CSMA/CA has been selected and standardized for intervehicle communication, as described in the next section.

2.2 ETSI Protocol Architecture for Intelligent Transportation Systems

In 2009, the European Commission issued a mandate (M/453) on the development of standards for cooperative safety systems based on vehicle-to-vehicle and vehicle-to-infrastructure communication. Therefore, as basic communication protocol, IEEE 802.11p has been adopted as a normative reference for the European profile standard for intervehicle communication. For the physical layer, OFDM-schemes with different modulation schemes are used in a Single Input Single Output (SISO) system. Multiple Input Multiple Output (MIMO) is part of advanced research (for example Molisch et al. [81]) to increase the wireless capacity, which is not taken into consideration so far in IEEE 802.11p.

On top, a protocol stack is currently under development in ETSI, CEN, and CENELEC. In the following, the intended architecture is reviewed. Based on that, the main functions of each layer will be explained with special focus on PHY and MAC layer. Note that some of the standards are about to be finished or currently under development by the time of writing this thesis.

2.2.1 ETSI ITS Communication Architecture

The communication protocol architecture foreseen for ITS is specified in the standard ETSI EN 302 665 [24]. Since ITS is not limited to vehicular communications, but also train, plane, and ship communications, the architecture is intended to be open and flexible. Thus, the architecture covers not only intervehicle communication but also access to public and private networks including the Internet as well as satellite broadcast.

An overview of the ITS station architecture is given in figure 2.2. The OSI layers 1 and 2 are comprehended by the Access layer. Layer 3 and 4 are covered by the Network and Transport layer, followed by the Facilities layer addressing the OSI layer 5, 6, and 7 functionalities. Next to the mentioned three layers there are the management plane