Multiscale Modeling of Inter-Vehicle Communication

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Zusammenfassung

Fahrzeug-zu-X (engl. Vehicle-2-X, V2X) Kommunikation besitzt das Potential, in absehbarer Zukunft die Abläufe auf unseren Straßen sicherer und effizienter zu gestalten. Fahrzeuge, welche zusätzlich zu Informationen der eigenen Sensoren auch auf kommunizierte Information von Nachbarfahrzeugen zurückgreifen können, sind in der Lage, den Fahrer umfangreicher als bisher zu unterstützen.

Vor dem Hintergrund stetig wechselnder, anspruchsvoller Umgebungsbedingungen und der sicherheitskritischen Bedeutung von V2X-Anwendungen nimmt die Zuverlässigkeit des Kommunikationssystems eine entscheidende Rolle ein. Sie ist sowohl für die Entwicklung von Komponenten und Protokollen als auch für die Beurteilung, inwiefern V2X-Kommunikation in der Lage sein wird, zu einem sichereren und effizienteren Straßenverkehr beizutragen, von zentraler Bedeutung.

Die Forschung und Entwicklung heutiger V2X-Systeme wurde hierbei maßgeblich durch Simulationen unterstützt, welche zur Bewertung von Protokollen, der Identifikation existierender Engpässe bis hin zu Folgenabschätzungen zum Einsatz kamen.

Die in den jeweiligen Simulationswerkzeugen eingesetzten Modelle unterscheiden sich jedoch oftmals, einerseits hinsichtlich unterschiedlicher Annahmen, auf die sie sich stützen, und andererseits hinsichtlich des umgesetzten Abstraktionsniveaus. Hierdurch ist nicht immer klar, welches Simulationsmodell für welche Betrachtung und welche abzubildende Situation geeignet ist, und es ist ebenso unklar, ob eine Konsistenz zwischen Modellansätzen, welche auf unterschiedlichen Abstraktionsebenen realisiert sind, gegeben ist. Während also einerseits unterschiedliche Modellierungsansätze für ein und denselben Aspekt existieren, so sind andererseits aktuell keine meso- und makroskopischen Modellansätze für den Einsatz zur Simulation von V2X-Netzen bekannt. Dies hat zur Folge, dass i) heutzutage immer noch keine V2X-Simulationsstudien in großem Maßstab durchgeführt werden können, bspw. um die Auswirkungen auf den Straßenverkehr eines Landes beurteilen zu können, und ii) ein tiefergehendes Verständnis darüber fehlt, welche Zuverlässigkeit durch das gegenwärtige Kommunikationssystem erreicht wird.

Die Beiträge dieser Dissertation adressieren diese beiden Defizite, indem neuartige Modellierungsansätze vorgestellt und existierende Ansätze miteinander verglichen werden. Weiterhin tragen die Beiträge zu einem tiefergehenden Verständnis der Zuverlässigkeit von V2X-Kommunikation bei und geben somit Hinweise für den Entwurf von zuverlässigen V2X-Anwendungen.

Die Radiowellenausbreitung beeinflusst entscheidend, über welche Distanz und wie zuverlässig eine Kommunikation zwischen Fahrzeugen erfolgen kann. Insbesondere in städtischen Szenarien unterliegt die Ausbreitung vielen Einflussfaktoren und es können starke Schwankungen auftreten. Eine akkurate **Modellierung der Charakteristik von Radiowellenausbreitung in städtischen Szenarien** ist somit entscheidend für die Eignung durchgeführter Simulationsstudien. Aus diesem Grund wird in dieser Arbeit zunächst ein Überblick über heutzutage eingesetzte urbane Radiowellenausbreitungsmodelle gegeben und deren Anwendbarkeit und Gültigkeit im Hinblick auf den Einsatz für V2X-Simulationsstudien diskutiert. Im Anschluss daran werden Grundlagen von Raytracing, einem sehr feingranularen Modellierungsansatz, vorgestellt und es wird erörtert, in welchem Rahmen Raytracing für Zuverlässigkeitsbetrachtungen in V2X-Netzen zum Einsatz kommen kann. Der Raytracing-Ansatz wird anschließend verwendet, um sowohl zu bewerten, in welchen Situationen welcher heutzutage eingesetzte Modellierungsansatz angemessene Ergebnisse liefert, als auch um eine Sensitivitätsanalyse durchzuführen, um die Situationen zu identifizieren, welche für zukünftige V2X-Anwendungen von besonderer Herausforderung sind. Die Ergebnisse zeigen, dass heutzutage eingesetzte Modellierungsansätze geeignet sind, durchschnittliche Ausbreitungscharakteristiken, wie sie bspw. für Betrachtungen auf Netzwerkebene von Interesse sind, angemessen abzubilden, wenngleich Situationen identifiziert werden, welche ggf. nicht individuell abgebildet werden können. Basierend auf den Beiträgen dieser Arbeit können sich zukünftige Studien fundiert für einen Modellierungsansatz entscheiden. Zusätzlich zu der bisher üblichen Betrachtung durchschnittlicher Kommunikationsbedingungen ermöglichen die Ergebnisse abzuschätzen, mit welchen Auswirkungen in Ausnahmefällen zu rechnen ist.

Die Zuverlässigkeit des Nachrichtenaustausches in V2X-Netzen hängt maßgeblich von der Fähigkeit des eingesetzten Medienzugriffsverfahrens (engl. Medium Access Control, MAC) ab, einen koordinierten Kanalzugriff in allen Situationen zu gewährleisten. Aufgrund der Charakteristik von V2X-Netzen, sich spontan zu bilden, stetig zu verändern und dennoch augenblicklich einsetzbar sein zu müssen, wird heutzutage ein dezentrales Koordinierungsverfahren favorisiert. **In dieser Dissertation werden zwei prominente Vertreter dezentraler Koordinierungsverfahren bewertet und miteinander verglichen** – das im IEEE 802.11p Standard definierte, auf Zufallszugriff basierende Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)-Verfahren und das auf Reservierungen aufbauende und im Schiffsverkehr eingesetzte Self-Organizing Time Division Multiple Access (STDMA)-Verfahren. Da STDMA im Gegensatz zu CSMA/CA bisher nicht im gleichen Umfang wissenschaftlich betrachtet und bewertet wurde, werden eine ausführliche Protokollbeschreibung zur Verfügung gestellt, existierende Stellschrauben erörtert und es wird diskutiert, welche in Fahrzeugkommunikationsnetzen auftretende Situationen dazu führen können, dass STDMA nicht in der Lage ist, den Kanalzugriff erfolgreich zu koordinieren. Um auftretende Paketkollisionen unmittelbar auf Protokollentscheidungen und die eingesetzten Protokollparametrierungen zurückführen zu können, werden hierfür zunächst perfekte Kommunikationsbedingungen angenommen. Im Anschluss daran wird eine

umfangreiche Parameterstudie durchgeführt, um zu identifizieren, wie häufig es zu Inkoordinationen zwischen Stationen kommt und wie sehr sich diese auf zukünftige Kanalzugriffsentscheidungen auswirken. Die hierdurch erzielten Ergebnisse erlauben i) die Situationen zu identifizieren, in welchen der auf Reservierungen aufbauende STDMA-Ansatz Stärken bzw. Schwächen im Vergleich zu CSMA/CA besitzt, und ii) eine für den Einsatz in Fahrzeugkommunikationsnetzen geeignete Parametrierung für STDMA zu identifizieren. Da die durchgeführte Analyse fundamentale Unterschiede offenbarte, wurde weiterhin untersucht, mit welchen Auswirkungen auf der Netzwerkebene zu rechnen ist. Im Speziellen wurde hierfür betrachtet, wie sich schwankende Kanalbedingungen und Mobilität auf die Koordinierungsgüte als auch die Netzwerkperformance beider Protokolle auswirken. Die Beiträge zeigen, dass der auf Reservierungen basierte STDMA-Ansatz unter schwankenden Kanalbedingungen vorteilhaft ist, da in der Vergangenheit empfangene Reservierungen in zukünftige Entscheidungen mit einfließen können. Unter Mobilität ist er jedoch nachteilhaft, da in der Vergangenheit getroffene Reservierungen eingehalten werden müssen, auch wenn sich bspw. in der Zwischenzeit die Umgebung eines Fahrzeugs geändert hat. Trotz dieser identifizierten und quantifizierten Unterschiede hat die Analyse gezeigt, dass die Unterschiede gering genug sind, um im Sinne eines makroskopischen Modellierungsansatzes für Fahrzeugkommunikationsnetze von einer konkreten Umsetzung abstrahieren zu können.

Die Verfügbarkeit von Informationen ist entscheidend dafür, ob eine V2X-Anwendung zuverlässig in der Lage ist, den Fahrer zu unterstützen. **Zur Modellierung der Informationsverfügbarkeit in Simulationsstudien wird eine informationszentrierte Modellierung vorgeschlagen**, welche im Gegensatz zu heutigen Ansätzen nicht zunächst alle Pakete modellieren muss, die zwischen allen Fahrzeugen im Netz ausgetauscht werden, sondern direkt für jedes Fahrzeug bestimmt, welche Informationen zu welchem Zeitpunkt in welcher Güte vorliegen. Ausgehend von dieser Idee wird im Anschluss ein empirisches, schnell berechenbares Modell vorgeschlagen, welches die Ausbreitungsverzögerung von einem beliebigen Start- bis zu einem beliebigen Endpunkt innerhalb eines V2X-Netzwerks bestimmt. Das Modell beruht auf einem "Teile und Herrsche"-Ansatz, in welchem das gesamte Straßennetz in elementare Bausteine, wie etwa Straßen und Kreuzungstypen, mit bekannter Ausbreitungsverzögerung unterteilt wird. Es konnte gezeigt werden, dass das Berechnen der Ausbreitungsverzögerung zwischen zwei beliebigen Punkten der Berechnung des kürzesten Pfades zwischen diesen entspricht. Um die Ausbreitungsverzögerung für eine Vielzahl dieser elementaren Baublöcke zu bestimmen, wurde eine umfangreiche Simulationsstudie durchgeführt, in welcher das Straßenlayout, Mobilitätsaspekte, Kommunikationsbedingungen und Eigenschaften des Kommunikationsprotokolls variiert wurden. Eine im Anschluss durchgeführte Evaluierung bestätigt die grundsätzliche Gültigkeit und zeigt auf, für welche Betrachtungen der vorgeschlagene Modellierungsansatz geeignet ist.

Abstract

Inter-vehicle communication is considered a promising approach to increase road safety and efficiency in the near future. Vehicles which do not solely have to rely on their own sensors to assist the driver, but are able to incorporate the communicated perception of other road users are able to make more profound decisions or are even able to negotiate cooperative driving strategies in a subsequent step.

Given the intended use cases of inter-vehicle communication as well as the harsh environment it is going to be deployed in, dependability of the communication system is of central importance for the development and decisive for the assessment of the overall system. Simulation-based assessment has hereby made important contributions, by evaluating and comparing protocols, identifying bottlenecks, or performing impact assessment. For this purpose, a variety of different simulation models have been proposed in the past, some of which address the same aspect, but on a different abstraction level or with some of them building on different assumptions. However, while on the one hand it is not always clear which situations are appropriately represented by which model and whether multiscale consistency is ensured across multiple layers, on the other hand, there is yet a shortcoming of mesoscopic and macroscopic models for the simulation of inter-vehicle communication. As a consequence, i) there is still uncertainty about the large-scale benefits of Vehicular Ad-hoc networks, and ii) a deeper understanding is missing in which situations the envisioned inter-vehicle communication system has its shortcomings with respect to dependability.

The contributions of this thesis are motivated by the objective of providing dependable inter-vehicle communication systems by demonstrating and contrasting different modeling approaches as well as increasing the understanding of how particular conditions or protocol features determine the characteristic and performance of inter-vehicle communication networks. Given the wide field of activities, we narrowed down our consideration to the following three multiscale modeling aspects, which decisively influence the dependability of the overall system:

From **radio propagation** to reception capability: Urban radio propagation conditions decisively influence how far and reliable vehicles can communicate in an urban environment and hence determine the fields of application of the envisioned inter-vehicle communication system. We first give a survey over urban radio propagation models which are currently employed within the vehicular networking community and discuss their applicability and validity. The principles of ray tracing, a fine-grained modeling approach, are discussed and we present how it can be applied for the purpose

of dependability assessment in inter-vehicle communication research. Subsequently, we employ ray tracing on the one hand to evaluate which simplified model yields appropriate results in which situations and on the other hand to study the general sensitivity of urban radio propagation conditions to various obstructions and hence to identify challenging conditions for future urban inter-vehicle communication applications. Our results show that even though situations, such as vehicles obstructing the line-of-sight, cannot be explicitly modeled by most currently employed statistical models, average radio conditions are appropriately represented, even in densely populated urban scenarios. The achieved results enable to assess the dependability of urban inter-vehicle communication by not just considering mean values, but also occurring outliers in future studies.

From **medium access control** to packet reception: The dependability of packet exchange in inter-vehicle communication networks heavily depends on the ability of the employed coordination scheme to successfully coordinate the channel access between participating stations under a variety of occurring circumstances, such as occurring decoding errors or the existence of interfering stations. For this reason, we assess and contrast the dependability of two prominent but fundamentally different decentralized coordination schemes – IEEE 802.11p Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Self-organizing Time Division Multiple Access (STDMA). In order to facilitate a profound analysis of STDMA we contribute a comprehensive protocol description and discussion of existing turning knobs as well as protocol elements that govern its function. We pursue a fundamental analysis of the STDMA protocol by first identifying situations in which, even though two stations are within each other's communication range, the STDMA protocol might not be able to successfully coordinate the channel, i.e., prevent concurrent transmissions by multiple stations. By means of an extensive simulation study we then quantify the likelihood of these situations to occur under a variety of parameters. These results help us to identify i) the main characteristics of STDMA in dealing with various situations and ii) how STDMA's protocol parametrization influences its capability to successfully coordinate the channel access in a vehicular environment. Since fundamental differences in strengths and weaknesses of both medium access control protocols became apparent, we subsequently investigate their cause and impact on a network level in more detail. In particular, we focus on understanding to which degree communication conditions, such as the severity of fading conditions, and mobility influences the coordination ability of STDMA compared to CSMA/CA and we hence contribute to an in-depth assessment of its dependability. Our results show that on the one hand the reservation-based approach of STDMA is beneficial under fluctuating channel conditions, since it allows to incorporate reservation information received in the past, on the other hand it is detrimental whenever there is a change of the vicinity, since STDMA requires more time to adjust to altered circumstances. Despite these differences, the obtained results justify to abstract from a specific protocol realization for macroscopic modeling approaches.

From packet level to **information level**: The availability of information determines whether a vehicle is reliably able to give advices to its driver. In order to address this issue, we propose an information-centric modeling concept which allows to directly model the availability of information in an inter-vehicle communication network without taking the detour of first having to model each and every packet exchanged in the network, as is done nowadays. Motivated by the vision to enable large-scale assessments, we subsequently present a light-weight modeling approach which can be employed within this modeling concept and allows to describe the dissemination delay within arbitrary inter-vehicle communication networks. The approach is based on the analogy of a construction kit where the road network is divided into elementary road segments, such as straight roads or intersections and whose characteristics w.r.t. the time it takes an information to traverse these blocks is known in advance. Determining the information delay is then just a matter of determining the shortest path between the information source and destination. In order to characterize and determine the traverse time for each block we perform an extensive simulation study, incorporating parameters related to the road network layout, mobility of the vehicles, communication conditions, and the data dissemination protocol. By means of an evaluation scenario, consisting of several of these building blocks, we show the general feasibility of this approach and discuss its applicability to enable future large-scale impact assessments of inter-vehicle communication.

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1
Introduction

The prospect to increase safety and efficiency on our road network by means of communicating vehicles have encouraged visionaries and researchers for a long time. Already at the World's Fair in 1939 the vision was raised that on highways in the 1960s, a "safe distance between cars is maintained by automated radio control". Then, 25 years later, in the World's Fair of 1964 a city of tomorrow was envisioned where "computer-guided vehicles would travel swiftly, safely, and efficiently" [Fer07]. While the general visions that were raised in these early years still remain valid nowadays, technical progress has tremendously changed the belief on how these can be realized.

The upcoming of widely available and cheap radio communication and positioning systems has led to a new renaissance in vehicular communication research in the early 1990s. Advances in microprocessor processing capacities further facilitated to shift the paradigm away from earlier envisioned centralized decision-making towards a decentralized concept where vehicles make use of Dedicated Short Range Communication (DSRC) to enrich their local views with information received from neighboring vehicles. The awareness range of a vehicle, which is traditionally limited by the range and possibilities of its own sensors, is consequently extended which allows a vehicle to propose more elaborate driving suggestions to its driver. A warning of an impending traffic jam can be given while there is still the possibility to take a detour or at least allows for a smoother approach towards the rear end of the standstill. A traffic light, broadcasting its scheduling time, enables approaching vehicles to advice their drivers of the required velocity to pass the intersection without having to stop at a red traffic light.

One key requirement for the deployment of inter vehicle communication systems at first hand and acceptance of the users in a subsequent step is dependability of the overall system (see [Lap95] for general concepts and terminology of dependability). While a belated advice to bypass a traffic jam might just be annoying and time consuming, an erroneous warning of an obstacle ahead might itself result in a dangerous situation. Consequently, dependability assessment plays an important role, not only in the design, but also for assessing the overall suitability of inter-vehicle communication systems to improve our road transportation system. A conclusive assessment hereby has to consider several aspects, such as the suitability of the underlying radio system, the ability of the employed communication protocols to cope with occurring packet losses and high mobility, as well as applications to reliably give timely advices and warnings to the driver.

Simulation-based assessment is an essential part in nowadays evaluation cycle and is generally included right from the start in today's development process. Achieved simulation results as well as resulting insights are, however, only valid and significant if the employed simulation model is an appropriate representation of the system under study with respect to a given issue. A consequent challenge for simulation-based assessment is hence to find an appropriate level of detail for respective research questions. While the resulting tradeoff between execution time on the one hand and accuracy on the other hand is already generally not answered easily, the multitude of involved domains and communities, which are working together in the field of inter-vehicle communication systems, even complicate this challenge. The interdisciplinary of this research area involves experts from the field of electrical engineering, operating on signals, over networking experts, interested in frames and packets, up to application engineers who are primarily interested in the availability of information. The simulation tools and models each community employs within their own domain is similarly oriented towards the same granularity and solely the respective layers are accurately modeled. For example, the Vehicular Ad Hoc Network (VANET) community, being focused on networking aspects in vehicular networks, puts great effort in accurately modeling the data link, network and transport layer, while lower layer characteristics are only considered statistically, at best. While on the one hand this abstraction level might be sufficient or due to runtime constraints even necessary for the evaluation of networking aspects in scenarios consisting of several hundreds of vehicles, it, on the other hand, might be too abstract for an accurate modeling of particular radio situations under consideration. On a different scale, but with the same rational a fine-grained modeling of the data link layer might not be reasonable or even feasible in order to perform impact assessment on traffic level in large-scale, e.g., for a country or state.

Given the multitude of distinct and often contradictory requirements, for instance what the simulation model is able to take into account compared to the execution time of the model and consequent scalability limitations, it is apparent that there is the demand to employ different model realizations of a single aspect within different domains or for different considerations. While obviously, differences between different model abstraction levels have to be expected, a certain model hierarchy consistency has to be ensured, i.e., important characteristics have to be preserved over multiple abstraction levels. While a multiscale modeling approach is nowadays quite common in various fields, e.g., in Physics for the simulation of fluids and solids [Ste07] or in Biology ([ANV07], [DM11]), its realization and applicability for the simulation of inter-vehicle communication has so far not been subject to research. As a consequence, on the one hand, it is not yet clear how the multitude of existing model realizations differ, which is of particular interest w.r.t. dependability assessment where these models are employed. On the other hand, there is still a lack of modeling approaches which allow to abstract from what is going on at the packet level and which hence enables the simulation of inter-vehicle communication on a meso- or macroscopic level. The contributions of this thesis address these two research issues and hence work towards answering the two motivational questions behind this thesis:

1. *Do currently employed modeling approaches for the simulation of inter-vehicle communication comply with the requirement of multiscale modeling, i.e., ensure a certain model consistency across multiple abstraction levels?*

2. *Which are the characteristics of inter-vehicle communication systems that determine various dependability aspects?*

1.1 Objectives

Within the scope of this thesis, these motivational questions are addressed within three different domains. The objective is hereby to contribute towards a multiscale modeling approach for the simulation of inter-vehicle communication systems by demonstrating new modeling approaches and quantifying expected deviations between different model hierarchy levels. On the other hand and with regard to the urgent necessity for dependability, the objective within each of these domains is to increase the understanding of how particular conditions or protocol features determine the characteristics and performance of inter-vehicle communication systems.

- **Urban radio propagation conditions:** Radio propagation conditions are a crucial factor in determining how far and reliable vehicles can communicate with each other. Besides the actual distance between a transmitter and receiver, there are plenty other influencing factors, e.g., whether obstructions block the line-of-sight path or how much vegetation is present which commonly urban radio propagation models, employed by the networking community, are not able to capture on an individual basis, but only statistically. As a consequence, even though the average behavior might be represented well, individual outliers which are crucial for determining the communication reliability/performance can be overlooked. While more fine grained propagation models exist, allowing the consideration of individual obstacles, their execution time behavior prevents their current use for network oriented research. Within the scope of this thesis, the first research question, comprising both motivational questions, can hence be stated as follows:

  Is the abstraction level of commonly employed urban radio propagation models appropriate for network oriented research?

- **Decentralized channel coordination:** In DSRC-based vehicular networks, participating vehicles have to share the medium amongst each other and coordinate in a decentralized fashion who is allowed to transmit at which point in time. Due to the rapid success of the IEEE 802.11 family [IEE12], a Carrier Sense Multiple Access (CSMA) approach was therefore pursued by the VANET community from the beginning. Carrier sensing based approaches basically employ a "listen-before-talk" principle, in which own transmissions are postponed in case the shared medium is sensed as busy. For a quite similar use case, the exchange of status information between ships [ITU10], respectively aircrafts [ETS11], a completely different MAC approach has been standardized: Self-organizing time division multiple access (STDMA), a reservation-based approach which preannounces own transmissions by attaching reservation information to previous transmissions. Quite recently, STDMA has also been proposed for VANET ([Sjö13], [ETS12]) and while first results look promising, there hasn't been a throughout analysis and understanding in which situations and to which degree substantial differences compared to CSMA have to be expected. Within the scope of this thesis our objective is to compare the current IEEE 802.11p standard with its most promising competitor for a decentralized channel coordination in inter-vehicle communication networks. This reveals the to be expected dependability which can be achieved by nowadays envisioned decentralized coordination schemes, but given their fundamentally different coordination approaches might further give indications in order to address the third research question of this thesis, which can be stated as follows:

  Can we abstract from a particular decentralized channel coordination scheme for a macroscopic modeling of inter-vehicle communication?

- **Information dissemination:** Being able to model the dissemination of information is one key requirement for assessing the benefits of inter-vehicle communication systems. Whilst in small-scale scenarios and typically for safety related use cases this can very well be done with existing packet-based simulation models, this approach does not scale well for the simulation of tens of thousands of participating vehicles, particularly due to large communication simulation runtimes. These large-scale scenarios, however, are a requirement for the evaluation of several efficiency related use cases, e.g., inter-regional route guidance that require the simulation of a large amount of vehicles, but is less demanding for an accurate communication modeling. The third research question within this thesis can hence be stated as follows:

  Can we macroscopically model the dissemination of information in inter-vehicle communication networks?

1.2 Contributions

Given the presented objectives and resulting research questions of this thesis, the contributions can similarly be structured into the same three domains. Across all three domains we pursued a common methodology which is briefly sketched in the following: First, we identified and assessed the properties which are most determining for the characteristic of the respective domain. Second, we evaluated whether existing modeling approaches are able to appropriately represent or cope with these, and third, if necessary and applicable, we proposed alternative modeling approaches to do so.

- From **radio propagation** to reception capability: In this thesis, a concept is presented which enables the use of ray tracing, a fine grained, but runtime expensive modeling approach, rather common within the electrical engineers domain, to be used for network oriented simulation studies. In order to cope with the immense runtime requirement of this approach, a pre-calculation approach is suggested and discussed. On the basis of a real world urban intersection scenario in the city of Karlsruhe, Germany, deviations between different modeling approaches are highlighted. We not only evaluate which currently employed simplified model yields appropriate results in which situations, but also the general sensitivity of urban radio propagation conditions to various obstructions and hence help to identify challenging conditions for future urban inter-vehicle communication applications. Furthermore, our approach enables to assess the dependability of urban inter-vehicle communication, not just by considering mean values, but also occurring outliers in future studies.
- From **medium access control** to packet receptions: In this thesis, a fundamental analysis of the suitability of STDMA, as an alternative to CSMA for the exchange of periodic messages in inter-vehicle communication networks is conducted. In order to achieve this, first, situations are identified in which, even though two stations are within each other's communicates range, the STDMA protocol might not be able to successfully coordinate the channel, i.e., prevent concurrent transmissions by multiple stations. In a second step we then quantify the likelihood of these situations to occur by performing a simulation study over a large parameter space. These results help us i) to identify the main characteristics of STDMA in dealing with various situations and ii) to characterize how the protocol parametrization of STDMA impacts its dependability in inter-vehicle communication systems. Since fundamental differences in strengths and weaknesses of both MAC protocols became apparent, we investigated their cause and impact on a network level in more detail. In particular, we focused on the influence of communication conditions, e.g., the severity of short-time fading conditions or various ranges up to which transmissions can still be carrier sensed, but no longer successfully decoded.
- From packet level to **information level**: In this thesis, an information-centric modeling concept which enables to employ multiscale models for inter-vehicle communication conditions is presented. The approach is highly customizable

by being able to support commonly employed packet-based simulation models, but also rather simplifying, but statistically still valid empirical or analytical communication models. A novel macroscopic model, to be used within the presented framework, is developed which allows to determine the time delay of information disseminated within an inter-vehicle communication network without the necessity to model the exchange of millions of packets, facilitating future large-scale assessments. The modeling approach is based on the analogy of a construction kit where the road network is divided into elementary road shapes, such as straight roads or intersections and whose characteristics w.r.t. the time it takes a packet or information to traverse these blocks is known in advance. Determining the information delay is then just a matter of determining the shortest path between the information source and destination/recipient. In order to characterize and determine the traverse time for each block we performed an extensive simulation study, incorporating parameters related to the road network layout, mobility of the vehicles, communication conditions, and the data dissemination protocol. By means of an evaluation scenario, we demonstrate the feasibility of this modeling approach.

Parts of the contributions presented in this thesis have been previously published in:

- T. Gaugel, L. Reichardt, J. Mittag, T. Zwick, H. Hartenstein; *Accurate Simulation of Wireless Vehicular Networks Based on Ray Tracing and Physical Layer Simulation*, In: High Performance Computing in Science and Engineering'11, Springer, 2012, pp. 619-630

- T. Gaugel and H. Hartenstein; *Appropriate Selection of Urban Vehicle-to-Vehicle Radio Propagation Models*, In: 21st IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT), Delft, Netherlands, 2014

- T. Gaugel, J. Mittag, H. Hartenstein, S. Papanastasiou, E. G. Ström; *In-depth Analysis and Evaluation of Self-Organizing TDMA*, In: IEEE Vehicular Networking Conference (VNC), Boston, USA, 2013

- T. Gaugel, J. Mittag, H. Hartenstein, E. G. Ström; *Understanding Differences in MAC Performance*, In: 15th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), Sydney, Australia, 2014

- T. Gaugel, F. Schmidt-Eisenlohr, J. Mittag, H. Hartenstein; *A Change in Perspective: Information-Centric Modeling of Inter-Vehicle Communication*, In: Proceedings of the Eight ACM international workshop on VehiculAr inter-NETworking (VANET), Las Vegas, USA, 2011

- T. Gaugel, J. Mittag and H. Hartenstein, *Characterization and Modeling of Dissemination Delays in Inter-Vehicle Communication Networks*, In: IEEE Vehicular Networking Conference (VNC), Seoul, Republic of Korea, 2012

1.3 Thesis Outline

This thesis is structured as follows: Following the opening chapter, comprising the thesis' objectives and contributions, Chapter II presents underlying inter-vehicle fundamentals. First, nowadays envisioned approach for "communicating vehicles" is presented in more detail, before a brief historic overview over the past decades of inter-vehicle communication research is given. Subsequently, challenges for the communication system are discussed, which arise on multiple layers, primarily due to harsh radio conditions that the system is deployed in. Following is a presentation of the state of the art protocol stack which is envisioned to cope with these conditions. A general introduction to evaluation and assessment of cooperative vehicular systems, with a particular focus on simulation-based assessment, but also briefly sketching conducted field operational test within the context of cooperative driving is given.

Subsequently to this general overview, the three main contributions of this thesis are presented in Chapter III, IV, and V, respectively.

Chapter III addresses whether currently employed urban radio propagation models abstract on the right level for network oriented research. First, an overview over existing urban radio propagation modeling approaches is given, before a brief introduction to ray tracing is given. Since ray tracing, contrary to commonly employed statistical models, allows for an individual consideration of radio obstacles, e.g., vegetation or vehicles obstructing the line-of-sight path, we perform a sensitivity analysis over various conditions. Subsequently, we i) contrast and evaluate in which situations simplified statistical models are able to capture resulting radio effects appropriately and discuss arising implications from the perspective of multiscale modeling, and ii) characterize the conditions which are most determining for the dependability of urban inter-vehicle communication.

In Chapter IV we address whether differences have to be expected if STDMA, a reservation-based coordination scheme, instead of the well known and widely used CSMA/CA scheme is employed for inter-vehicle communication systems. Existing coordination schemes, which all try to coordinate the periodic transmission of multiple stations in a wireless network are introduced and prerequisites are discussed. Following is an in-depth analysis of STDMA, by first identifying situations in which STDMA is not able to successfully coordinate two stations, even though they are within each other's communication range. We then quantify these situations to occur by presenting results from an extensive simulation study and characterize how STDMA's parametrization influences its coordination ability in a vehicular environment. The strengths and weaknesses of STMDA in comparison to CSMA/CA are subsequently analyzed by considering various conditions which a medium access control scheme has to master within the context of vehicular networks, such as severe fading conditions or high mobility. This chapter concludes with a discussion on whether differences have to be expected for inter-vehicle communication applications if a different coordination scheme is being employed and whether from the perspective of multiscale modeling it is possible to abstract from a particular medium access control protocol.

In Chapter V an approach is presented which allows to directly model the dissemination delay within an inter-vehicle communication network, i.e., macroscopically model the view a vehicle possesses on its vicinity, without having to consider the exchange of each and every packet exchanged in the entire inter-vehicle network. First, it is discussed how inter-vehicle communication simulation-based assessment is conducted nowadays. Then, we present an information-centric modeling approach which enables to employ multiscale models for the simulation of inter-vehicle communication. Based on the motivation to facilitate large-scale assessments of inter-vehicle communication networks, we present a novel light-weight information dissemination modeling approach. Since model building of this approach required an extensive simulation-based study, we subsequently present the underlying characterization of the information delay within inter-vehicle communication networks, w.r.t. to mobility, road network layout and communication condition aspects. Finally, evaluation results are shown that help to quantify the differences that have to be expected, compared to traditional packet-based simulation approach. Finally, we discuss for which considerations this novel approach offers an appropriate level of abstraction.

Finally, Chapter VI concludes this thesis and gives directions for future research.

2

Research Fundamentals & Methodological Challenges

This chapter provides a foundation for the three following chapters by providing an overview over fundamentals of the currently envisioned communication system as well as discussing methodological challenges in the field of inter-vehicle communication. We therefore first adhere to the historic development of inter-vehicle communication systems and discuss step-by-step how technical achievements have steadily changed the vision of inter-vehicle communication systems. Subsequently, aspects and challenges which need to be addressed by the communication system are discussed and nowadays envisioned standards are presented. Finally, methodological challenges w.r.t. evaluating and assessing inter-vehicle communication systems are presented.

2.1 Overview

The idea of inter-vehicle communication is by far not new. Already in 1923 Harry Flurscheim filed a patent for a *radio warning system for use on vehicles* with the United States Patent Office. Within the patent US1612427 [Flu26] which was patented in 1926, the system is described as follows:

> "The present invention relates to radio warning systems for use on vehicles intended to permit a vehicle to signal its presence by means of electric waves to all other vehicles in its more or less immediate vicinity, equipped with similar or equivalent apparatus and devices, particularly to such vehicles located in front or on the side of the vehicle signalling its presence and facing in the approximate direction of said signalling vehicle."

Even though this vision was pushed forward in the following years by introducing it to the general public as a future vision for tomorrow's highways at the World's Fair in 1939, technological shortcomings prevented the realization of communicating vehicles for quite some time. Whilst the motivation to increase safety and efficiency as well as reduce road traffic's ecological footprint has remained unchanged over all these years, technological achievements restricted what was actually feasible.

Starting in the 1950s, first envisioned concepts required a signal-emitting control band, integrated into the road surface, to communicate with and control the vehicle which was not practicable due to resulting infrastructure costs. In the 1970s interest emerged all over the world in advanced route guidance systems which employed inductive loops for a communication between road side stations and passing vehicles. Passing vehicles were given route advices, based on current traffic conditions and their destination. These systems where never deployed in large scale which was due to necessary investments cost, but also reasoned by technological deficits, e.g., low transmission rates. A brief historic overview over some milestones of almost a century of inter-vehicle communication research is therefore presented in Section 2.2.

Starting in the 1990s, research in vehicular communication has experienced a new renaissance with the upcoming of widely available and cheap radio communication and positioning systems. Particularly, advances in short range communication systems, which led to the success of the IEEE 802.11 family [IEE12] and the publicly availability of the Global Positioning Systems[1] led to new visions and concepts in vehicular communications, but also for the transport system as a whole.

This is also reflected by the term Intelligent Transport System (ITS) which was formed and comprises the use of communication means not only to improve road traffic, but in a multi-modal and multi-user fashion to improve the transport system as a whole. This broader scope is as well indicated by the definition of the European Parliament and of the Council within the directive 2010/40/EU:

> "Intelligent Transport Systems" or "ITS" means systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, and in traffic management and mobility management, as well as for interfaces with other modes of transport.

Within this thesis, however, our focus is on inter-vehicle communication as such and we do not explicitly consider multi-modality, i.e., communication abilities between different means of transport. Within this given setting, nowadays commonly pursued concept is the increase of a driver's awareness by making use of direct vehicle-to-vehicle and vehicle-to-infrastructure communication. While a driver's awareness about its vicinity is generally limited by its viewing range and hence prone to curves, fog, or buildings, obscuring the sight at intersections, vehicular communication can help to fill existing gaps and extend the maximum possible awareness range. Periodic messages, exchanged between participating vehicles hereby serve as a basis (for

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[1] GPS system description of the United States Naval Observatory (USNO): `ftp://tycho.usno.navy.mil/pub/gps/gpssy.txt` [last visited in December 2015]

building up neighborhood awareness), which is then extended by received event messages, transmitted by neighboring vehicles in exceptional situations, e.g., under harsh braking. Such an awareness database is locally maintained by every vehicle and in case of an impending dangerous situation, an indication or warning is given to the driver who can react appropriately. Besides obvious safety related benefits, efficiency improvements are possible as well, since a driver can be given more up to date information on its travel route ahead and potential alternatives. Traffic lights which communicate their scheduling time can furthermore help reduce emissions, since it allows approaching vehicles to calculate the necessary speed at which the intersection can be passed without having to stop. As can be seen, the communication system has to fulfill various requirements, such as being reliable and having a low latency for safety related use cases up to having a large dissemination range for efficiency related use cases. The envisioned communication system is based on Dedicated Short Range Communication (DSRC), but can be complemented and assisted by cellular systems as well (where applicable).

Whilst the general concept of nowadays inter-vehicle communication system sounds rather straightforward, there are many challenging aspects that such a system and, in particular, the communication system has to master. Contrary to the conditions that the IEEE 802.11 family was originally designed for, the radio conditions in vehicular networks are more severe and can change rapidly, e.g., due to strong fading and shadowing effects (cf. Mecklenbräuker et al. [MMK+11] for an overview over recently conducted vehicular channel measurements). Consequently, the physical layer has to be rather robust and be able to rapidly adjust to temporal radio fluctuations. The network layer, being responsible for coordinating the channel access, is additionally challenged with high mobility and consequent rapid changes of a vehicle's vicinity and the prerequisite for a decentralized coordination scheme. Section 2.3 presents existing challenges which exist on various layers of the communication system in more detail. The fundamentals of the currently envisioned protocols for a first generation of inter-vehicle communication networks and, in particular, how they are designed to cope with existing challenges are subsequently presented in Section 2.4.

Traditionally, researchers in the field of inter-vehicle communication solely relied on simulation-based assessment for the design, optimization and evaluation of their protocols and applications. Only recently, with the maturing of inter-vehicle communication standards, particularly the IEEE 802.11p standard [IEE10a], first field operational tests (FOT) were carried out. While these are an invaluable source, e.g., for demonstrating the interoperability between different marks and brands or for investigating the robustness, simulation-based assessments remain essential. Amongst others, it enables to assess and compare protocols under constant conditions, e.g., same radio and traffic conditions and generally allows for an easier scaling up, compared to the acquisition of new vehicles and drivers in FOTs. Section 2.5 points out the vital importance that simulation-based assessment plays in nowadays research and development process and discusses existing challenges. In particular, challenges which are related to choosing a simulation model with an abstraction level appropriate for the objective under consideration as well as approaches to perform holistic ITS research by incorporating communication, mobility, and application aspects are discussed. Additionally, an overview of the focus and some results which were achieved in recent cooperative vehicular system FOTs are given and briefly discussed.

One aspect which is not considered in detail within this thesis is the performance of applications, building on top of the envisioned communication protocols, as well as the subsequent impact on traffic. Bridging the gap between network performance and traffic impact is a research field on its own and has to incorporate multiple aspects. In a first step, quite apparently, vehicular communication applications, similarly to underlying protocols, have to be able to handle i) unreliability of wireless communication, but to a larger extend also ii) uncertainties, e.g., due to sensor inaccuracies or unknown behavior of neighboring vehicles, but still be able to give reliable advices or warnings in every situation. Then, in a second step, it has to be considered whether the informed driver reacts appropriately and the impact on traffic level has to be estimated. Since the requirements as well as traffic impact of every vehicular application is different, this is a rather elaborate process. In order to close the gap between communication performance and application requirements the concept of *awareness* has been used in the literature ([SMS+11], [AGH11]), which quantifies how well the communication performance satisfies specific application requirements, for instance, a maximum information distance or minimum required update interval.

2.2 A Brief History on Inter-Vehicle Communication

It is a huge leap from the first visions raised almost a century ago and nowadays generation of inter-vehicle communication systems. Tremendous amount of research, technological improvements, projects, and demonstrations have been performed with some milestones being presented in the following.

First serious technical explorations and concepts in the field of "Automated Highway Systems (AHS)" date back to the 1950s in the United States [Wet03]. General Motors and the Radio Corporation of America initiated collaborative research and a first concept car, the Firebird II[2] was presented in 1956 which was thought to be controlled and communicating via a signal-emitting control band integrated into the road surface. Only two years later, first successful technical demonstrations took place ([Wet03], [Ben91]), but technical limitations prevented a continuation of research within the industry [Wet03]. Several years later, academia picked up AHS research, e.g., at the Ohio State University in 1964 [FM91].

The emerging of more advanced radio technologies in the following years led to new research and projects, particularly in the United States, Japan and Europe in the 1970s, with a focus on advanced route guidance systems. The Electronic Route-Guidance System (ERGS) [RMF70] in the US was the pioneer, employing an inductive loop based two-way communication system to exchange destination information from the vehicle to a road side station and resulting routing advices backwards. In Japan, the Compre-

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[2] `https://www.gmheritagecenter.com/gm-vehicle-collection/1956_Firebird_II.html` [last visited in December 2015]

hensive Automobile Traffic Control System[3] (CACS) [Tot80] project was conducted in between 1973 and 1979 with the general idea of incorporating up-to-date road status information which was collected by means of vehicular communication from vehicles passing a roadside station. Quite similar attempts were followed in Europe, more particular in Germany, in the 1970s with the ALI-System [Bra80](“Autofahrer-Leit- und Informationssystem”) or in the early 1980s with the AUTO-SCOUT system [Tom84] which was based on infrared technology. Both approaches were later combined in the ALI-SCOUT system [Tom91].

A next research wave in vehicular networking started in the mid 1980s. In Japan, an improved route guidance system, the Road/Automobile Communication System (RACS) [IMK+91] based on radio communication in the 2.5 GHz band was developed and first experiments on vehicle-to-vehicle communication were conducted by JSK (Association of Electronic Technology for Automobile Traffic and Driving). In Europe, the extensive PROMETHEUS (Programme for a European Traffic of Highest Efficiency and Unprecedented Safety, 1987-1995) project was initiated by EUREKA with multiple research directions [Wil88], two of them being vehicle-to-vehicle and vehicle-to-infrastructure communication, which were explored within the sub projects PRO-NET [DH88] and PRO-ROAD, respectively. While a majority of today’s envisioned communication system still traces back to ideas originating from these projects, the radio communication and location technology was not mature enough in these early years. In 1989 the European Union funded its own first telematics research program DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe) with a total of 72 projects and the vision for a Europe “in which drivers would be better informed and in which intelligent vehicles would interact with their surroundings”[4].

In the US, the PATH program explored and evaluated possibilities in the fields of navigation, automation, and roadway electrification and in 1992 first platooning experiments were performed [Shl06]. Contrary to the EU and Japan, there was no national program in the US, several stakeholders, however, formed the Mobility 2000 consortium to promote Intelligent Vehicle Highway Systems [Cas89]. Even though, first accomplishments and successful demonstrations were achieved in the 1980s, the technological basis was not mature enough, i.e., there were deficits in communication, positioning and computing performance for a deployment.

Then, in the mid 1990s technological capabilities tremendously improved with the standardization of IEEE 802.11 [IEE97] in 1997 and the publicly availability of the Global Positioning System. The focus of the research efforts changed towards cooperative assisted driving, with communication technology assisting the driver in making more founded decisions. In 1999 the United States Federal Communication Commission accelerated further research in the area of vehicular communication by allocating a spectrum of 75 MHz in the 5.9 GHz band for DSRC systems.

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[3] `http://www.toyota-global.com/company/history_of_toyota/75years/text/entering_the_automotive_business/chapter2/section2/item5.html` [last visited in December 2015]

[4] `http://cordis.europa.eu/telematics/tap_transport/research/16.html` [last visited in December 2015]

In the ongoing years, vehicular communication research tremendously increased under the term Intelligent Transport Systems (ITS) which can be seen in plenty of research projects in the EU, e.g., the Inter-Vehicle Hazard Warning project within the years 2001 and 2002 [Che02], the communication platform oriented FleetNet Project [Enk03], or the WILLWARN project [HHSV07] demonstrating the feasibility of a hazard warning system building on top of vehicle-to-vehicle communication. Similar activities were as well ongoing within the US, for instance to identify the applications which are enabled by inter-vehicle communication [The02], as well as in Japan with the Advanced Safety Vehicle project, starting in 1991 and meanwhile being in its fifth phase.

In 2008, the European Telecommunications Standards Institute followed this interest by allocating a 30 MHz spectrum within the 5.9 GHz band to be used for Intelligent Transportation Systems within the EU. An extension of the IEEE 802.11 standard for use in vehicular environments was published in 2010 as IEEE802.11p [IEE10a].

For a more comprehensive overview over past inter-vehicle communication activities we refer to [TB09].

2.3 Aspects and Challenges of Inter-Vehicle Communication Systems

A prerequisite for inspiring the confidence of road users towards inter-vehicle communication is that advices are given reliably as well as in time. While wrong efficiency related advices, e.g., to bypass a traffic jam which has already vanished might just be annoying for the driver, an erroneously advice to brake hard might in the worst case result in a dangerous situation itself. The resulting implications on safety will hereby even tremendously increase when progressing from currently envisioned cooperative assistance systems towards autonomous driving.

In contrast, it is in the nature of wireless communication that reliability cannot be guaranteed, even in well-known and consistent office environments. In a vehicular environment, however, the communication system is even challenged more by a highly dynamic and harsh environment. The goal of achieving a reliable (as far as possible) assistance system thereby comes along with understanding the challenges and aspects the communication system has to master. Possible challenges hereby originate from the depths of radio propagation conditions up to the application layer where decisions have to be made on, for instance, whether non up-to-date information is sufficient to warn a driver of an impending situation. A non exhaustive overview on existing challenges, as well as possible approaches on how they can be addressed on multiple layers, is hence discussed in the following.

2.3.1 Physical Layer

Challenges for the physical layer directly emerge from the underlying characteristics of the radio channel. A brief introduction to these effects, as well as implications for the physical layer, w.r.t. to the Orthogonal Frequency Division Multiplex (OFDM) based IEEE802.11 physical layer, is given and discussed in the following. For a more detailed overview we refer to [TB09] and [Mit12].

A packet, traversing the physical layer is divided into bits which are transferred to signals and then transmitted over the air. One signal is hereby transmitted for a period of one *symbol time*. On a receiver this process is basically processed in reverse. Whether a packet can in the end be successfully decoded hereby depends on multiple characteristics. At first glance, the path loss between a transmitter and potential receiver is one of the most crucial ones. It characterizes the attenuation of a transmitted signal until it arrives at the receiver and hence directly influences the signal strength which is determining whether the receiver is able to successfully decode it or even be able to detect it at first hand. A higher path loss thereby generally indicates "worse" conditions. The path loss itself is influenced by several aspects: i) the direct decay of the signal due to free-space loss, ii) interactions along the way, such as reflections or diffractions at a house facade, iii) shadowing effects, e.g., buildings obstructing the line-of-sight path, and iv) multipath propagation effects, which are due to signals propagating over multiple paths and these constructively or destructively overlapping at the receiver. From the perspective of the physical layer, there is, however, not much that can be done about it. A threshold has to be selected at which a signal is considered to be strong enough to synchronize to it - if chosen too high, potential successful receptions are non attempted, while if chosen too low, highly unlikely successful receptions are attempted, which might prevent synchronizing to a stronger signal within its reception time.

Besides the path loss, there are several more channel characteristics which further influence whether a signal and consequent packet can be successfully received. The delay spread, originating from multipath propagation, characterizes in a timely manner the (mean and max) excess delays of a signal which "arrives" at a receiver, being propagated over multiple paths. Strong delays can be problematic in several ways: On the one hand, the resulting signal strength can vary a lot in the course of one symbol time, due to superposition of waves. On the other hand, there is even the possibility that subsequent symbols are influenced in case the maximum delay exceeds the *guard interval*, the time between two distinct transmissions. This effect is called intersymbol interference and has to be addressed by the physical layer by an appropriate selection of the guard interval.

Doppler spread characterizes a quite similar phenomena, but this time on the frequency domain. Multiple reflections arriving at the receiver, but with different angles result in a spread of the signal energy in frequency. This can generally be problematic, since transmissions on adjacent frequencies can be influenced. For this reason, the physical layer has to ensure a sufficient carrier spacing to prevent intercarrier interference. In addition to a careful selection of guard intervals and carrier spacing, a physical layer should continuously adjust to current radio conditions to cope with delay and Doppler spread [AHG07]. On the one hand, this can be achieved by a periodic transmission of training symbols and on the other hand sub carriers can solely be used as pilot tones to learn the current conditions and adjust equalization algorithms accordingly.

2.3.2 Data Link Layer

The data link layer consists of two sublayers, the logical link and media access control(MAC). The logical link control is nowadays primarily responsible for multiplexing, i.e., forwarding the received frame to the appropriate network layer. The media access control has then again multiple tasks, including the addressing scheme and coordinating which station is allowed to access the media at which point in time. Multiplexing can quite easily be done by information which is present in the LLC header and addressing on the link layer can be done by MAC-addresses, which are already assigned by the hardware manufacturers, if necessary. Coordinating the media access is hence the main challenge for the data link layer.

Considering the principle paradigm of inter-vehicle communication networks, a decentralized coordination scheme is inevitable. As a consequence, coordination decisions are based on local perceptions and thus influenced by regional or short-term radio variations as well as prone to hidden terminal situations. Since there is no general solution to avoid these issues within the considered environment, it is even more important that stations are able to cope with occurring packet collision, i.e., the MAC protocol has to be able to still successfully coordinate the channel even under occasional packet collisions. Additionally, dynamics, due to vehicular mobility or strong fading continuously changes the perceived vicinity of a vehicle and hence makes it necessary for the protocol to adaptively adjust to it.

A further challenge arises, since the MAC layer has to be able to adjust to large variations of participating nodes. In a rural scenario, only several vehicles within the vicinity might be present, while in a congested highway or urban scenario easily more than 200 vehicles can be existent. Under both situations the MAC protocol has to ensure the required capability, e.g., by being able to adaptively adjust the numbers of transmissions per vehicle. Since nowadays idea of inter-vehicle communication comprises the periodic exchange of status messages as well as exceptional messages in case a hazardous event is imminent, there has to be the possibility for i) additional transmissions at short notice, and ii) preferably a higher priority for the transmission of safety critical messages. Particularly for these event messages, but also in general, the existence of a maximum delay before the message is forwarded to the physical layer to be actually transmitted is desirable. Additional fairness mechanisms on the MAC layer could furthermore ensure that every vehicle gets an equitable share of the media.

Common criteria which are considered for MAC protocols generally refer to optimizing the throughput, reducing the delay, offering quality of service, ensuring fairness between stations, and increasing robustness under fluctuating conditions. These requirements are likewise valid in a vehicular environment, whereby the robustness is generally challenged the most.

2.3.3 Network, Transport and Application Layers

Generally, the network and transport layers in a vehicular environment are challenged in a similar way than the MAC protocol. The forwarding and routing task is particularly burdened with high dynamics and occurring packet losses. Contrary to traditional ad-hoc networks, where forwarding paths are generally either built up by proactive protocols, such as OLSR [CJ03], or reactive ones, such as AODV [PBRD03], both approaches are not suited in a vehicular environment, due to high mobility and low delay requirements for safety related messages. Additionally, the employed protocols have to support the following communication paradigms which are applied in inter-vehicle communications for various use cases/applications:

- Broadcast: Status messages, e.g., containing the vehicle's speed, location, and direction are periodically sent out to neighboring vehicles. They serve as the basis for an increased awareness and are not forwarded by receiving vehicles. As a result of the high rate of this packets to be transmitted, a low network layer overhead is essential.
- Anycast / Geocast: Employed to address one or every vehicle within a certain geographical location. An intended purpose is to inform succeeding vehicles on the same highway timely about an upcoming traffic jam. Since the common communication range of one hop broadcast messages is therefore not sufficient, the messages have to be forwarded to the destination area. Based on the high relevance of this paradigm for inter-vehicle communication, this topic has undergone a lot of research(e.g., [FWK+03],[MWH01]).
- Unicast / Multicast: Currently less envisioned for safety or efficiency related use cases, these paradigms might become of interest for fleet management or infotainment use cases, for instance. Instead of addressing a geographical area, particular vehicles are addressed.

Based on the one hand on the variety of paradigms that have to be supported and on the other hand reasoned by the general characteristics of inter-vehicle communication conditions, it becomes apparent that the employed protocols have to be robust, adjustable, but also light weight, i.e., be rational with the available resources.

In traditional wired networks, the transport layer has the task to avoid or if already present, dissolve congestion on the channel. As already previously mentioned, inter-vehicle communication networks are as well prone to congestion, for instance in congested highway scenarios. For this reason, the load every vehicle is generating has to be limited in a fair and decentralized fashion to avoid oversaturation of the channel and as a consequence an increased loss of (safety related) messages. There are generally two ways of how this can be achieved. First, the number of periodic messages which are sent out every second can be limited by the transport layer or by means of a cross-layer design by already reducing the number of generated CAMs at first hand. Second, the transmit power can be reduced, limiting the dissemination area of the own transmissions and hence relieving the channel load. Those interested in scalability issues of inter-vehicle safety communication are referred to [Tie14] for further considerations.

It is the application's task to evaluate the current situation and if applicable give an indication or warning to the driver. The decision process therefore generally incorporates information of other vehicles, received by means of communication, but also information of its sensors, e.g., the own speed or current position. Based on non reliable communication and uncertainty in sensor quality, the application has to decide reliably, timely, and independently whether a warning should be given. In [AMH14] it is exemplarily gone through the design of a fail-safe rear end collision avoidance application and difficulties are pointed out.

2.4 State of the Art

This section briefly gives an overview over the protocols which are currently envisioned for a first generation of inter-vehicle communication networks. The overall protocol stack, as being standardized in the US and Europe is presented first in Section 2.4.1, while Section 2.4.2 gives a brief summary of the IEEE 802.11p protocol.

2.4.1 Protocol Stack Overview

Due to the increasing interest in ITS and the conviction that safety and efficiency on our roads benefits the most if there is a mutual "language spoken" by every vehicle, standardization bodies all over the world have adopted this topic. Slightly different protocols and standards have thereby emerged, the most prominent ones being the IEEE 1609 standards (WAVE) in the United States [IEE14] and the ETSI TC ITS standards in Europe [ETS10]. Despite several differences, for instance the existence of GeoNetworking on the network layer, similarities are apparent on physical and medium access layer, where in both cases the IEEE 802.11p standard is being employed and the envisioned or already allocated frequency range is quite similar - 5.850-5.925 GHz in the US and 5.855-5.925 GHz in Europe[5]. Both standards specify the periodic exchange of status information (containing a vehicle's speed, position, heading and more) which serve as a basis for safety applications and are denoted Basic Safety Message (BSM) in the US and Cooperative Awareness Message (CAM) in Europe. In case a hazardous situation is detected, the European standard foresees the transmission of a Decentralized Environmental Notification Message (DENM) which can furthermore be forwarded to distant locations where appropriate. In the following, an overview over the scope of the IEEE 1609 standard is exemplarily given.

IEEE 1609 (WAVE) standard

The IEEE 1609, also known as Wireless Access in Vehicular Environments (WAVE) standard, ranges from lower up to higher layer specifications, as is depicted in Figure 2.1. The IEEE 802.11 standard is being deployed for the physical layer as well as medium access control and is presented in more detail in the next Section. The IEEE 1609.4 standard deals with multi-channel operations which enables to make use of several 10 MHz channels within the allocated 75 MHz band at 5.9 GHz. One associated use case is that vehicles periodically listen to a so called control channel

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[5] at the time of writing, the 5.855-5.875 GHz band has only be recommended by the Electronic Communications Committee to be used for non-safety ITS communication services in Europe, but has not been allocated so far (cf. ECC/DEC/(08)01)

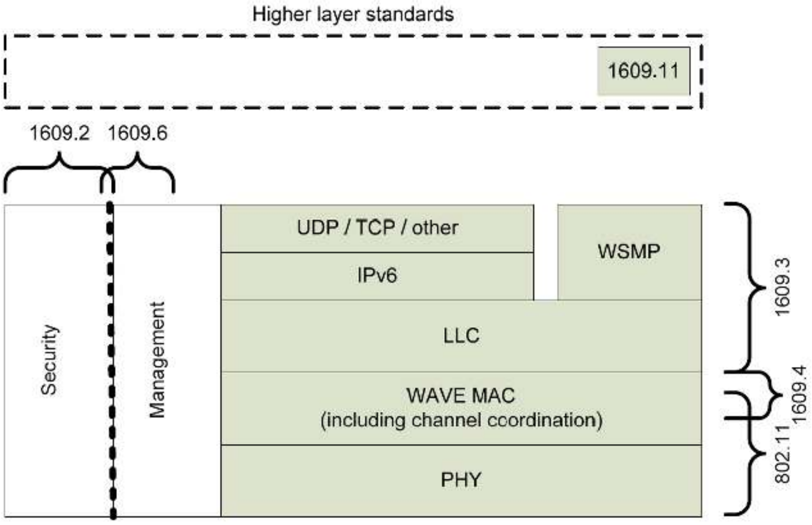

Figure 2.1: Overview of the IEEE 1609 standard [IEE14] (©2014 IEEE)

where they learn about information of general interest, but also about specific interests on a multitude of differing service channels. A station is then free to switch to one of these service channels, e.g., depending on subjective relevance for the driver, for a fixed amount of time before returning to the control channel. The focus of the IEEE 1609.2 standard is to provide mechanisms to ensure authentication, integrity, authorization, or confidentiality for the applications at their request. Obviously, employing these mechanisms has to come in hand with the envisioned use case, i.e., an encrypted warning message is of no use if approaching vehicles are not able to decrypt it. IEEE 1609.3 deals with network services, for instance the use of regular IPv6 for non safety related applications or the WAVE Short Message Protocol (WSMP), which is a light-weight one hop protocol. Contrary to the European ETSI TC ITS, the IEEE 1609 does currently not standardize driver assistance applications, with the exception of 1609.11 which describes an electronic ITS-based payment protocol.

A more detailed overview over inter-vehicle communication standardization within the United States as well as in Europe can be found in [Sjö13]. For a more profound insight we refer to the standardization bodies of ETSI, CEN, IEEE, ISO, or SAE directly.

2.4.2 The IEEE 802.11(p) Standard

The success of the IEEE 802.11 family in the early 2000s inspired research towards an extension for wireless access in vehicular environments. A first draft was published in 2005 and it was finally standardized as IEEE 802.11p in 2010. It consists of an architectural view on the physical as well as data link layer, in correspondence with respective layers of the OSI reference model. The IEEE 802.11p standard is basically based on the IEEE 802.11a standard with several adjustments to make it more robust against radio fluctuations that have to be expected in a vehicular environment. It was finally integrated into the current revision IEEE Std 802.11-2012 [IEE12] in 2012.

The first generation of inter-vehicle communications is currently envisioned to be based on the IEEE 802.11p standard whose characteristics are briefly summarized in the following. The **physical layer** is equal to the Orthogonal Frequency-Division Multiplexing (OFDM) based physical layer of IEEE 802.11a with a channel bandwidth of 10 Mhz and supporting data rates from 3 Mbps with BPSK coding up to 27 Mbps with a 64-QAM coding scheme. Currently, it is envisioned to employ a maximum data rate of (only) 6 Mbps which has been shown to be the most suitable trade off between robustness against interference on the one side and capacity on the other [JCD08]. The available channel bandwidth of 10 MHz is split into a total of 52 subcarriers, each separated by a subcarrier frequency spacing of 0.15625 MHz and guard intervals of 1.6 μs to ensure robustness against occurring radio variations, due to previously mentioned Doppler or multipath propagation effects.

A carrier sense multiple access with collision avoidance (CSMA/CA) approach serves as the basis for **medium access control** in the IEEE 802.11-2012 standard. The so called distributed coordination function (DCF) has to be implemented by every station and constitutes the minimum requirement that every station has to fulfill. Within the DCF mode there is no central coordination, but stations decentralized coordinate themselves by means of a random access scheme.

The "carrier sensing" hereby constitutes a key role, since stations first have to listen to the channel and decide on whether a transmission is currently ongoing. In case the medium is sensed as being not occupied for the duration of an inter-frame space (the minimum time interval between two frames), the station is allowed to transmit immediately. In case the current sensed signal level exceeds an arbitrary configured carrier sense threshold (*physical carrier sensing*), the channel is declared to be busy and the transmission is postponed. Independently of the current signal level, the same applies if the station's network allocation vector indicates a current ongoing transmission(*virtual carrier sensing*), which can be due to information given in the duration field of a previously decoded MAC header (even though the station was not able to decode the payload). Given that the medium is sensed as being occupied, the transmission attempt is deferred at least until the ongoing transmission has ended plus an inter-frame space and extended with some additional random backoff time. The goal of the random backoff is to reduce contention conflicts which would otherwise occur with high probability right after a transmission has ended, since every station with a postponed transmission would attempt to access the medium right away at the same time. For this reason, every deferred transmission has to pick a random number which equals a specific backoff time. The backoff time is then decremented as long as the medium is sensed to not be occupied and the transmission starts as soon as the counter reaches zero. In case the medium is sensed as being occupied in the meantime, the timer is paused for this times span and resumed afterwards to avoid starvation of single stations.

The basic principle of the decentralized DCF coordination scheme is visualized in Figure 2.2 by means of a simple scenario. First, Station A wants to transmit a packet which it is immediately allowed to do so after the medium is not occupied for a time span of *DIFS*. Within the transmission period, stations B and C want to transmit a packet themselves, but have to defer the access, since they sense the

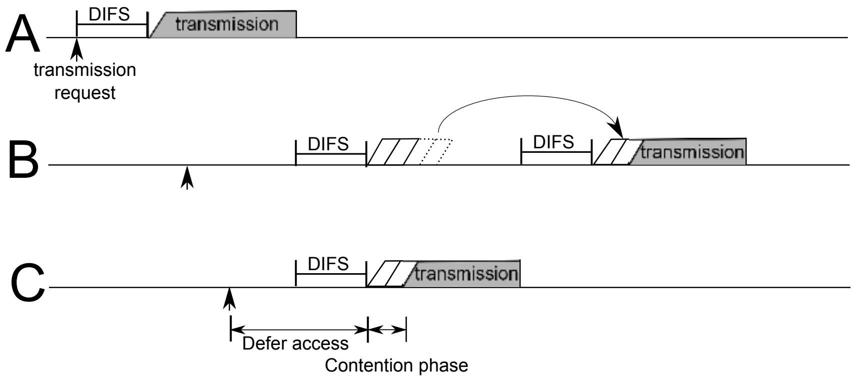

Figure 2.2: Basic principle of the IEEE 802.11 CSMA/CA decentralized coordination scheme

medium as being occupied. After the medium is sensed as not being occupied again (for a duration of one *DIFS*), the contention phase begins in which both stations independently pick a random backoff slot and start decrementing towards it. As soon as the first station reaches its chosen slot, this station is allowed to transmit (Station C) and the other station has to defer again (Station B) for the transmission period. Station B continues decrementing the previous backoff timer after the medium is sensed as being not occupied again.

Consequently, the decentralized coordination function of IEEE 802.11 does not employ direct communication between participating stations to coordinate which station is allowed to access the medium at which point of time, but a random access scheme is being used. The absence of explicit coordination information has several advantages: Packet losses or even simultaneous transmissions are per se no harm for the coordination ability of the DCF, since it only has to be able to detect ongoing transmissions and does not have to be able to decode its content to successfully operate. Besides the own backoff counter no states are kept, which makes this approach rather spontaneous in adapting to new scenarios, e.g., rapidly changing vicinities.

Owed to more than 20 years of rigorous treatment, the DCF coordination scheme is well understood by now and the impact of its parametrization has been extensively studied. The carrier sense threshold, for instance, indicates the aggressiveness of a station when performing a transmission attempt - the lower it is configured, the more “cautious” a stations behaves (e.g.,[SBL$^+$11], [SCB11a]). The contention window is another turning knob whose optimal size depends on the current load - if it is too small, there is a high probability of simultaneous timeouts and hence concurrent transmission attempts, if it is too large, stations have to wait unnecessarily long, reducing the overall throughput and increasing delays (cf. [RvEKH11], [Eic07]). While in traditional IEEE 802.11 networks, the contention window is exponentially increased over consecutive transmission attempts, this approach is not applicable for a vehicular environment, where most transmissions are of broadcast nature and hence no direct feedback is available. An appropriate initial selection of the contention window is hence crucial for the overall suitability of the vehicular communication system. The standard hereby foresees a size of 15 backoff slots with a time interval of 13 μs each.

In order to support the prioritization of transmissions, which is for instance of interest for voice over IP applications in a home network, but also for safety related warning messages in vehicular networks, the IEEE 802.11-2012 standard furthermore comprises four optional coordination extensions. Apart from an infrastructure-based coordination scheme, the point coordination function (PCF), which basically polls its associated stations and is hence not suited for a deployment in a vehicular environment, there is also a decentralized approach, the enhanced distributed channel access (EDCA). It is basically an extension to DCF and replaces the uniform inter-frame spaces of DCF with ones that are inversely proportional to the corresponding service levels, i.e., higher priority traffic has shorter inter-frame spaces and thus shorter waiting times on average. Additionally, the previously discussed contention window size is adjusted, depending on the access level (priority) of the to be transmitted data. For high priority data, a smaller contention window size is used, resulting in shorter waiting times and reasoned by the fact that only a small portion of the overall data is of high priority. This approach is envisioned to the employed as a quality of service mechanisms for vehicular communication. Furthermore, there are two hybrid coordination schemes, HCCA and MCCA, which both alternate between a centralized coordinated contention free period and a contention period where an approach similar to EDCA is being employed. Due to the non existence of a centralized coordinator these approaches are again not applicable in a vehicular environment.

2.5 Evaluation and Assessment

Evaluation and assessment is of central importance in nowadays research and development processes. Technical suitabilities of a technical system have to be validated prior to roll out and stakeholders are interested in a cost benefit analysis before making investments. In general, there are several evaluation methods, including experimenting with the real system, a miniaturized copy of it, e.g., with remotely operated miniature vehicles, or by performing simulations. Depending on the scope of the analysis, but also by the availability and maturity of the technical components under consideration, an appropriate method has to be selected. In the field of vehicular communication networks, the prospects of miniaturizing are limited which is due to the impossibility to miniaturize certain aspects, such as radio propagation conditions. Experiments with the real system have been performed in the early years, e.g., by means of demonstrations, but also quite recently by means of field operational tests with the purpose to show the interoperability as well as robustness of the developed vehicular communication systems. Simulation-based assessment, however, has contributed the major part for the development of ITS systems by offering a cost-effective possibility to repeatedly experiment with a system which primarily only existed on paper.

In the following, we will hence first give an overview over simulation-based assessment approaches in the field of inter vehicle communication in general. The intention is to provide a foundation for particular simulation models, which are employed within the field of the three contributions of this thesis, and are presented in later chapters. Following in Section 2.5.2 is a brief summary over recently conducted field operational tests.

2.5.1 Simulation-based assessment

Simulation-based assessment is a crucial building block which has been employed for various aspects during the development of nowadays vehicular communication systems. Its field of applications ranges from i) quantifying the technical suitability of, for instance, routing protocols, over ii) comparing alternatives, e.g., different parametrization of the MAC protocol, up to iii) performing impact assessment, for instance by quantifying whether safety gains can be expected for our road transportation system.

There are several benefits of performing evaluations by means of simulations: the system under consideration does not necessarily have to exist, constant conditions, which are a prerequisite for fair comparison, can be ensured and it offers a rather flexible and cost-effective evaluation approach, compared to performing field operational tests.

Simulation models

The biggest challenge generally arises with respect to the validity of the employed simulation models. Achieved results are only valid and significant if the underlying simulation model is an appropriate representation of the system under consideration - might it be a particular protocol or the transportation system as a whole. In 1962 Russel L. Ackoff characterized models as

> "They are idealized in the sense that they are less complicated than reality and hence easier to use for research purposes. These models are easier to manipulate and "carry" than the real thing. The simplicity of models, compared with reality, lies in the fact that only the relevant properties of reality are represented." [Ack62]

Abstracting from non key factors hereby generally serves two purposes: i) amplifying knowledge gain by focusing on the most determining influencing factors and ii) achieving a manageable complexity and hence acceptable execution time behavior which makes a knowledge gain feasible in the first hand. Abstractions, generally result in a reduced accuracy of a model, which has been appropriately summarized by George E. P. Box as:

> "Essentially, all models are wrong, but some are useful." [BD86]

Identifying an appropriate level of abstraction for the research questions under consideration and selecting corresponding simulation models is hence a key task which has to be performed before conducting a simulation study. As already discussed previously, there is a general trade off between what the simulation model *is able to represent* vs. its *execution time* behavior and hence scalability limitations. While, for instance, in order to optimize the physical layer the consideration of multipath propagation effects is inevitable, their impact might be neglectable for measuring the traffic-related impact of inter-vehicle communication systems or might even prevent its feasibility on a large-scale. Generally speaking, while there is the desire to consider each and every influencing factor for specific research questions within a particular domain, this is no longer feasible for holistic considerations of inter-vehicle communication systems and appropriate simplifications have to be found.

Within the field of inter-vehicle communication the commonly level of abstraction, however, is rather uniformly a packet as the considered unit for communication simulation and individual vehicles for traffic simulation. While more abstracting modeling approaches exist in the field of traffic simulation, by well established meso- and macroscopic models, there are yet no equivalent approaches existent for communication simulation.

Simulators

A simulator is the executive unit of a simulation model. It performs a simulation study by applying the starting conditions as well as input changes over time to the employed simulation model, keeps track of its internal states and commonly outputs some kind of result in the end. Generally, simulators bundle multiple simulation models of a specific domain into one package, allowing a user to select its preferred model realization as well as combining multiple aspects. Communication simulators, for instance, often comprises models for the entire communication stack - from radio propagation modeling over network modeling and sometimes even up to simplistic application models. Nowadays common representatives for simulating communication aspects of inter-vehicle communication systems are the Network Simulator 3 (NS-3)[6], OMNeT++ [VH08], or JIST/SWANS[7].

While these simulators are commonly employed for packet-based simulations, meaning that the smallest considered unit is a packet (or as a matter of fact a frame), there are no fundamental limitations that prohibit to go beyond a packet level simulation. NS-3, for instance, has been extended by a more fine-grained physical layer implementation [MPHS11] which is operating on bits and symbols instead of entire packets. The additional execution time of this more accurate representation is stated to result in a slow down factor of up to 7 000 due to computationally expensive signal processing. Quite recently, OMNeT++ was also extended with a more fine-grained physical layer model, operating on packets, bits, or symbols, as requested[8]. The other direction, abstracting from the exchange of individual packets and going towards an information-centric perspective is, so far, not realized.

Simulator coupling approaches

While in the early years of inter-vehicle communication research, there was a clear focus on communication aspects, the focus has shifted in recent years towards more holistic considerations, incorporating as well mobility, driver behavior, and application aspects. Communication simulators, which have been traditionally employed for inter-vehicle communication research, are on their own no longer able to cover all necessary aspects. Simulator coupling is one approach which has been followed by the ITS community to enable the joint consideration of multiple aspects of inter-vehicle communication. In general, several different approaches have been realized in the past to combine communication and mobility aspects for the simulation of inter-vehicle communication systems:

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[6] `http://www.nsnam.org/` [last visited December 2015]

[7] `http://jist.ece.cornell.edu/`[last visited December 2015]

[8] `https://github.com/inet-framework/inet/blob/v2.99.1/WHATSNEW`[last visited December 2015]

1. *Offline coupling:* In case there is no direct feedback involved between the communication and traffic simulator, an offline coupling approach can be pursued. The traffic simulator generates a traffic trace which contains the speed as well as position of each and every vehicle within the road network with a predefined timely resolution, e.g., one second. The communication simulator reads in the trace file and places its nodes at the corresponding positions, according to the simulation time. In case more frequent position updates are required by the communication simulator, the position of a node can be interpolated based on the two nearest traffic trace snapshots. An advantage of this approach is that acknowledged simulators for both disciplines can be employed and that no additional synchronization overhead between both simulators is necessary. As previously mentioned, this approach does not allow for a feedback between both simulators, i.e., the traffic simulator is not able to adjust the driver behavior, e.g., braking behavior or route choice, based on information exchanged via inter-vehicle communication. Consequently, this approach is of rather restricted use for the assessment of ITS systems.

2. *Single simulator:* Integration of driver behavior modeling into the communication simulator or vice versa. A dedicated traffic or communication simulator is extended with models to forge a single simulator incorporating both disciplines. This approach is for instance followed by [AW10] by including the Intelligent Driver Model(IDM) [THH00] into NS-3. Despite its general applicability and simplicity for exchanging data between both simulation domains, this approach is rarely pursued nowadays, which might be reasoned by having to self-reliantly model aspects from different disciplines, instead of being able to employ acknowledged simulation tools.

3. *Integrated simulation tool sets:* Coupling of multiple simulation tools into one evaluation and assessment framework. Lochert el al. [LBC+05] were among the first to propose a joint simulation environment, consisting of the network simulator NS-2 [9], the traffic simulator VISSIM[10], as well as Matlab/Simulink[11] for application modeling.

   More recently, several simulator coupling approaches with more flexibility and extendability have been proposed for ITS research. While nowadays employed integrated tool sets all have specific distinguishing characteristics, the architectural concept commonly follows the High Level Architecture (HLA) concept, which is standardized in IEEE1516 [IEE10b]. A runtime engine interconnects the participating simulators and interoperability is usually ensured by obeying to interface specifications which enables to replace individual simulators. A general architectural overview of the traditional HLA architecture applied to

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[9] `http://www.isi.edu/nsnam/ns/` [last visited in December 2015]

[10] `http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/` [last visited in December 2015]

[11] `http://www.mathworks.com/products/simulink/` [last visited in December 2015]

the simulation of inter-vehicle communication systems is presented in Figure 2.3. The VSimRTI [QSR08] and iTETRIS [KLK⁺10] integrated tool sets are being two popular representatives for the simulation of ITS. While VSimRTI follows the HLA concept more closely, by employing a standardized framework and hence allowing the exchange of individual simulators, the iTETRIS framework focuses on the dedicated coupling of the NS-3 network simulator and the vehicular traffic simulator SUMO [KEBB12].

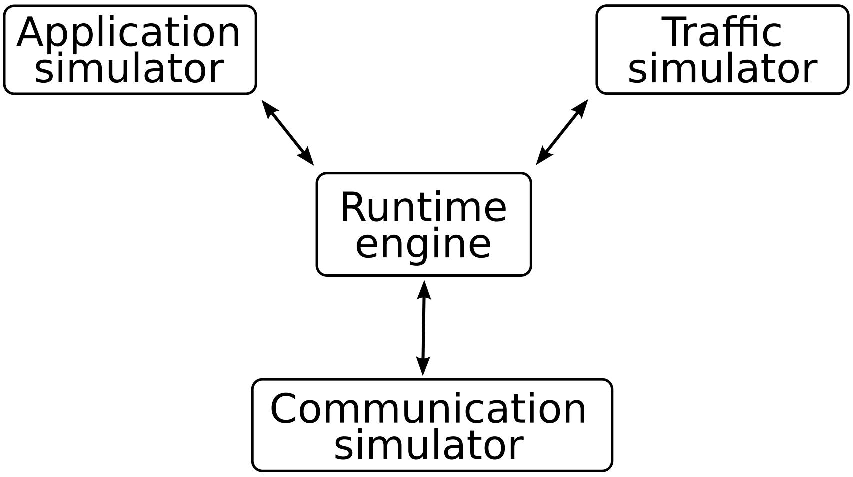

Figure 2.3: Basic principle for the simulation of intelligent transportation systems by making use of the High-Level Architecture. An application, traffic and communication simulator is coupled through a runtime engine which is responsible for the timely synchronization and data exchange between participating simulators [IEE10b].

Discussion

The steady increase of simulator coupling approaches over recent years illustrate that there is a consensus within the inter-vehicle communication community to bring every aspect together and provide a solid foundation for application and traffic engineers to contribute in ITS research. A loose simulator coupling approach further enables multiscale simulation by being able to easily exchange individual simulators and hence simulation models. Yet, the steps which have been taken are not sufficient to allow for comprehensive ITS research, especially w.r.t. to large-scale assessment. On the one hand, a loose coupling of simulators creates non negligible overhead related with synchronization and is hence not efficient w.r.t. the overall simulation runtime performance. On the other hand, the employed simulators and more particularly the applied communication simulation models are still solely based on the consideration of individual packets. This fixed granularity prevents an arbitrary scaling of the simulation study in order to answer nowadays research topics. We can hence summarize that while simulator coupling approaches are a step in the right direction to enable holistic ITS research, they are on their own no universal tool to address nowadays issues without appropriate simulation models.

2.5.2 Field Operational Tests

Field operational tests are another method for the evaluation and assessment of envisioned inter-vehicle communication systems. Compared to simulation-based assessment there are different perspectives and incentives involved to conduct a field operational test. The focus hereby generally lies on aspects, such as i) interoperability of a system between different brands, ii) proving the market maturity of a system, iii) showing or validating the user acceptance of a system, or iv) performing impact assessment which is quite challenging by means of simulations, since aspects, such as psychological driver behavior is hard to model appropriately. Given the high costs of field operational tests as well as their preparation time, this approach is generally pursued subsequently to a pre-validation by means of simulation. Furthermore, there are additional issues that need to be considered before and while performing a FOT, e.g., legal issues or one has to carefully design its tests and performance indicators, since realizing that necessary data is missing after the tests (when evaluating the data) is too late. The FESTA handbook [FOT14] points towards further issues and presents a general methodological framework for FOTs. Apparently, before a system is deployed and rolled out on our roads, it has to overcome both evaluation approaches which is why simulation-based evaluations and field operational tests complement each other instead of being mutually exclusive.

In the following, a brief overview over recently conducted field operational tests of cooperative systems is given:

- **sim**^{TD} (2008 - 2012)[12]: German FOT with a primary technical focus. Overall more than 100 test vehicles, another 300 additional vehicles to create required traffic conditions as well as more than 100 roadside stations were involved. A large variety of safety, efficiency, and convenience related functions were developed, with aspects starting from the detection of particular traffic situations, processing within vehicles, communication via IEEE 802.11p or cellular systems, as well as the Human Machine Interface(HMI) for displaying the information to the driver. The FOT was supported by a parallel conducted simulation-based assessment to quantify the impact on a traffic level.

- **SCORE@F** (2010 - 2013)[13]: French FOT with a total of 42 vehicles on 3 test sites. Its primary goals were the preparation of a large-scale future FOT and evaluation of the technical suitability of the communication system. Hereby, a minimum coverage range of 300 meters with vehicle-to-vehicle communication and up to 1.3 km for vehicle-to-infrastructure communication was reported. By means of several safety related functions, the FOT evaluated the user acceptance and found it in need of improvement, since advices could not always be given timely and reliably.

- **SISCOGA** (2009 - 2011): Spanish FOT with the goal to prepare and implement a Spanish *intelligent corridor* to evaluate cooperative systems. A total of 60 highway kilometers were therefore equipped with 30 roadside stations and

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[12] `http://www.simtd.de/index.dhtml/enEN/index.html` [last visited in Dec 2015]

[13] `https://project.inria.fr/scoref/en/` [last visited in December 2015]

20 vehicles performed first evaluation runs with a focus on safety and efficiency related functions [SDB+12].

- **DriveC2X** (2011 - 2014)[14]: European Commission funded integration project to ensure the interoperability of nationally developed systems and to join the findings which have been collected on test sites all over Europe. In total more than 200 test vehicles were involved which drove more than 1.5 million kilometers. Within this project we contributed i) by performing a simulation-based pre-validation of test scenarios, which were then later conducted during the FOT, ii) by assessing the communication performance under a variety of situations, and iii) by scaling up the achieved results on an EU-level. The overall results predicate positive safety effects, e.g., a reduced number of accidents and fatalities, even with low penetration rates [Con14].
- **Connected Vehicle Safety Pilot (USA)** (2011 - 2013): Large-scale FOT in the US with up to 3 000 participating vehicles whereby only a small subset (≈ 10%) of vehicles were equipped with a HMI to give advices to the driver, the remaining vehicles were equipped with transmission only devices, i.e., only broadcasting periodic status messages. The main objectives of this FOT were to evaluate the suitability of the currently envisioned communication system to support safety related functions and identify their safety potential[15]. It was concluded that already the deployment of only a subset of two vehicle-to-vehicle safety related functions (Intersection Movement Assist, Left Turn Assist) are able to prevent 25 000 to 592 000 crashes annually [HPY+14] and that there is a high user acceptance of more than 90%. The results collected within this FOT have influenced the NHTSA decision on initiating a rulemaking that would eventually mandate inter-vehicle communication capabilities for light vehicles in the US in the future[16].

2.6 Summary

In this Section a brief introduction to inter-vehicle communication was given. First, the underlying idea and envisioned concept was presented, before the history and development of the preceding years was sketched. Challenges that arise from harsh conditions that the system is deployed in, e.g., strong fluctuating radio conditions or consistent changes of the vicinity, were subsequently discussed with the focus of how the communication system is designed to overcome these challenges. The currently envisioned communication system, based on the IEEE 802.11 standard and its integration into the IEEE 1609 (WAVE) protocol stack was presented. The central role that simulation models possess in nowadays development process was discussed and it was pointed out that it is essential to utilize models with an abstraction level, appropriate for the research question under consideration.

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[14] `http://www.drive-c2x.eu/` [last visited in December 2015]

[15] `http://www.its.dot.gov/research/safety_pilot_overview.htm` [last visited in December 2015]

[16] `http://www.nhtsa.gov/staticfiles/rulemaking/pdf/V2V/V2V-ANPRM_081514.pdf` [last visited in December 2015]

3
Urban Radio Propagation Modeling

In this chapter, we are addressing the first research question of *whether the abstraction level of commonly employed urban radio propagation models are appropriate for network oriented research.* After a short introduction and overview about the necessity for an appropriate radio propagation modeling, we briefly present the underlying physical principles. Afterwards, we review related work with the focus of pointing out different urban radio propagation modeling approaches that are employed for the simulation of ITS systems.

In order to address the raised research question, we, on the one hand, evaluate which situations currently employed statistical models are able to represent, i.e., to which degree the respective simplified models can be parametrized (Section 3.2.2). On the other hand, we employ fine-grained ray tracing in order to perform a sensitivity analysis in Section 3.3 with the focus to evaluate to which degree radio obstacles, such as vehicles or vegetation obscuring the line-of-sight, influence radio communication conditions in an inner city scenario and hence to identify the situations which are most critical for future urban inter-vehicle communication applications. The insights of both sections are then utilized in the following section in order to compare and evaluate to which degree currently employed simplifying path loss models are able to capture significant influencing factors and hence we identify which model yields appropriate results in which condition. Subsequently, we evaluate whether key essences are retained across multiple abstraction levels not only by means of the path loss, but also by an assessment of the packet delivery ratio and packet inter-arrival time.

Parts of this chapter have been previously published in [GRM+12] and [GH14].

3.1 Motivation

Radio propagation conditions are a crucial factor in determining how far and reliable vehicles can communicate with each other or with a road side unit (RSU) and hence decisively determine whether inter-vehicle communication applications are able to give timely and reliably advices to drivers in a subsequent step. With an extended communication distance, a vehicle might more timely become aware of, e.g., a broken down vehicle and is able to inform its driver earlier, potentially resulting in a smoother approach. While for this considered use case, a one time reception of a message from the broken down vehicle itself or being forwarded by other vehicles might be sufficient, there are also use cases where regular updates are vital. Advising a driver to brake harshly, e.g., by a forward- or intersection collision avoidance system, should be based on up-to-date information about the "opponent" and not be based on rather outdated information that were received 10 seconds ago. For this reason, not only the earliest distance at which a communication is possible has to be modeled correctly, but also how reliable from this point on a communication can take place. Similarly, for an application it can be of crucial difference whether packet losses occur occasional or "en bloc".

An appropriate modeling of radio propagation characteristics are consequently a prerequisite for a proper assessment of the dependability of the overall system and in a subsequent step also for the design of various aspects, such as communication protocols or applications. According to the IEEE standard 211, radio wave propagation is defined as: "the transfer of energy by electromagnetic radiation at radio frequencies" [IEE98]. Besides the attenuation of the transmitted waves over distance (according to an inverse-square law), every wave can be subject to various phenomena, like reflections, refractions, diffractions, or scattering along the way. These effects collectively alter the original wave by adding additional attenuation (e.g. due to being reflected) and furthermore "splits" the original wave, resulting in multiple propagation paths which can interfere at a potential receiver. The so called *multipath interference* can hereby either be constructive or destructive, depending on the phase difference between arriving waves. Its characteristics as well as resulting impact within the context of urban radio propagation is considered in Section 3.3.

In the following we employ the term radio propagation for solely characterizing the channel in between a transmitter and receiver, without the consideration of additional aspects, such as for instance the radiation characteristics of the antenna. In the field of vehicular communication an isotropic antenna is commonly considered, which distributes its power evenly in all directions. The underlying principle is based on the assumption that the position of vehicles which are most interested in the distributed information cannot be known a priori to a transmission. However, in case the position of potential receivers is known in advance, for instance when communicating with a roadside station or only addressing vehicles on a particular road segment, directional antenna systems are able to reduce interference (cf. [NSD+07], [NYYH00]). The overall effect of particular antenna installations is typically stated as *equivalent isotropically radiated power(EIRP)* and includes the transmission power, potential antenna gain, or cable attenuation.

Generally, the primary means of propagation is determined by the frequency of an emitted radio wave. While for low frequency transmissions and typically for large distance communication, the propagation process is supported by reflections at the ionosphere (see [Joh62]), the direct wave or path between the transmitter and receiver is the most determining factor for high frequencies, such as for the 5.9 GHz band, the frequency standardized for use in vehicular communication networks. Furthermore, while low frequency waves are able to penetrate several objects, such as bricks, absorption effects become more crucial at higher frequencies, limiting the ability to communicate "through the corner" and hence relying on communication "around the corner" for vehicular communication. Respective radio propagation models for use in urban scenarios consequently have to be able to at least consider this *non line-of-sight* communication means.

The focus of the following state of the art radio modeling section is i) to give an overview on urban vehicle-to-vehicle radio propagation models, which are commonly employed by the vehicular networking community, and ii) to illustrate its applicability and potential limitations.

3.2 Related Work: Urban Radio Modeling Approaches

An accurate modeling of radio conditions in vehicular environments requires the consideration of multiple aspects, such as the path loss, multipath propagation, and Doppler effects. As previously discussed in Section 2.4.2, guard intervals and inter-carrier spacing of the OFDM layer of IEEE 802.11p are designed to cope with interference between different data symbols due to different propagation paths and with frequency shifts due to the Doppler effect in most conditions. Multipath propagation, however, also effects the signal strength and phase due to superposition of waves within the transmission of one data symbol. While on a signal level these impacts are often prominent, their impact diminishes on a network level where the forward error correction and QPSK modulation scheme of IEEE 802.11p makes it rather robust against occasional variations. For this reason, the vehicular networking community generally only explicitly models the path loss when performing simulation-based assessments on a network perspective. In the following we adhere to this approach, since additional characteristics, such as frequency shifts or Doppler spread could anyhow not directly be considered in traditional packet-based network simulators.

Modeling of the path loss can generally be separated in three levels of influence, each with a different rate of change, as, for instance, is pointed out in [PFMnEn08] and [SAZ07].

1. **Free-space path loss** of the signal as it is disseminated in space and without consideration of any radio obstacles. The received power hereby declines according to an inverse square-law with an increase in transmitter-receiver separation. Due to its primarily visible effect over large distances, we use the term *large-scale path loss* synonymously and interchangeable in the following.

2. **Shadow fading** is attributed to shadowing effects which occur under non free-space propagation, due to radio obstruction at the surrounding environment and can tremendously influence the reception strength. The resulting impact at two receivers, both being equidistant to a transmitter can hence vary significantly, but its effect is assumed to be rather constant for a distance of several wavelengths ($\lambda \approx 5cm$ @ $5.9\,Ghz$). Generally, it is assumed that the coherence time of a large-scale fading channel is longer than the symbol time, i.e., there is no variation during the transmission time of one symbol.

3. **Multipath fading** attributes to the effect of multipath propagation within a small scale (e.g. within one wavelength) and represents the constructive as well as destructive effects on the resulting path loss. The coherence time is thereby assumed to be less than the symbol time, i.e., the channel characteristic can change within the transmission of one symbol.

While already in a closed and simplistic scenario the deterministic consideration of all these effects is sophisticated, it is no longer feasible in an open world scenario where exact characteristics of radio obstacles cannot be known. Within the vehicular networking community there is hence a common consensus to statistically model the vehicle-to-vehicle radio channel. Rappaport characterizes the modeling of the radio channel in a similar fashion as:

> "Modeling the radio channel has historically been one of the most difficult parts of mobile radio system design, and is typically done in a statistical fashion, based on measurements made specifically for an intended communication system or spectrum allocation" [Rap01]

A nowadays common approach is hence to find mathematical expressions for previously mentioned three influencing factors which are summed up to determine the overall path loss between a transmitter and receiver in the end. Generally, two different model building approaches are therefore pursued: i) analytical considerations, which model the propagation channel based on physical principles, and ii) empirical considerations, which are built based on finding a best fit of real-world measurements. While empirical models hence implicitly consider previously mentioned aspects, they have to be modeled explicitly for analytical modeling approaches. It should be kept in mind that in commonly employed packet-based simulations, the channel is assumed to be constant within one packet transmission, i.e., no varying multipath propagation effects are considered within the transmission of one packet. Corresponding models for representing the path loss characteristic are presented in the following, while Section 3.2.2 gives a brief overview of related work which addresses the applicability and validity of existing urban radio modeling approaches.

3.2.1 State of the Art

Analytical considerations:

Most nowadays employed large-scale path loss models are still based on, or derived from the Friis free space path loss model [Fri46] which assumes idealistic radio conditions, i.e., unobstructed radio wave propagation in space. According to Rappaport [Rap01] the received signal strength $P_r(d)$ in dBm at distance d can be calculated with the Friss free space equation as follows:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{3.1}$$

where P_t is the transmission power, G_t and G_r are antenna gains of the transmitter and receiver, respectively, λ being the wavelength and L ($L \geq 1$) being a system loss factor with a value of 1 representing a lossless system. The separation distance d between transmitter and receiver contributes quadratically to the path loss, as can be seen by looking at the denominator. The Friis free space path loss model has been extended by several means, e.g., resulting in the Two Ray Ground model (cf. [Rap01]) which further incorporates an additional ground reflection path. The consideration of this additional propagation path generally results in multipath interference which can have a severe constructive or destructive overall effect on the path loss, particularly at close distances. Several network simulators, however, implement the Two Ray Ground model in a simplified way, by applying the Friis free space path loss calculation up to a cross-over distance d_c which is for instance calculated by NS-3[1] as:

$$d_c = \frac{4 * \pi * h_t * h_r}{\lambda} \tag{3.2}$$

where h_t and h_r are the respective antenna heights of the transmitter and receiver and λ being the wavelength of the to be transmitted signal. In case the distance exceeds the cross-over distance, the received power of the two ray ground model is then calculated by:

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{3.3}$$

with P_t being again the transmission power, G_t and G_r possible antenna gains, h_t and h_r antenna heights and L the loss factor. It should be emphasized that the separation distance d hereby contributes quartic to the decline of the signal strength. Within the domain of inter-vehicle communication, with resulting low antenna heights and rather high frequencies, the crossover distance results in $\approx 500\,m$ with the implication that for most inter-vehicle communication conditions the Friis free space path loss model is being employed. Sommer et al. [SJD12] hence lately proposed a more sophisticated model realization, the two-ray interference model, which considers the interference of this ground reflection path in more detail in close distance and found its effect to be non neglectable for simulation-based assessment.

While previously presented propagation models allow for a consideration of the free space path loss as well as the consideration of the impact of a simplified multipath fading in case of the two ray interference model, these approaches are not suited

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[1] `https://www.nsnam.org/docs/release/3.23/doxygen/classns3_1_1_two_ray_ground_propagation_loss_model.html` [last visited in December 2015]

for urban scenarios since they do not allow to take shadowing effects into account. Their consideration, however, can have a severely detrimental impact, particularly in urban scenarios where there is often no direct line-of-sight communication path between two stations and communication relations are only enabled by means of non line-of-sight communication.

The analytical CORNER urban radio propagation model ([GFPG10], [GFPG11]) therefore differentiates between line-of-sight and two non line-of-sight situations: communication around the corner and to a vehicle on a parallel street. For line-of-sight conditions the free space attenuation formula is used, while for non line-of-sight conditions the model basically calculates the path loss based on the power decay of a signal over distance, in combination with the number of reflections and potential diffraction a signal is subjected to before arriving at a receiver. The CORNER model is hereby based on the model proposed by Sun et al. [STT05], which proposed the analytical approach and verified it by means of real-world measurements. The path loss in line-of-sight as well as non line-of-sight on a perpendicular road is hereby calculated based on the formulas stated in Equations 3.4 and 3.5:

$$PL_{LOS}(d) = 20 * log\left(\frac{\lambda}{4 * \pi * d}\right) \tag{3.4}$$

$$PL_{NLOS}(d_{Tx}, d_{Rx}) = 10 * log\left[\left(\frac{\lambda}{4\pi}\right)^2 * \frac{\lambda}{4d_{min}d_{max}^2} + \left(\frac{\lambda}{4\pi(d_{Tx} + d_{Rx})}\right)^2 * 10^{\frac{L_W N_{min}}{10}}\right] \tag{3.5}$$

with λ being the wavelength and d representing the distance between transmitter and receiver in line-of-sight conditions. For non line-of-sight conditions the formula is composed of two components, with the first one representing the diffraction component and the second one the reflection component. In non line-of-sight conditions, the distance d_{Tx} represents the distance from the transmitter to the intersection center and d_{Rx} represents the distance from the intersection center to the receiver. The minimum of d_{Tx} and d_{Rx} is termed as d_{min} and the maximum of both values as d_{max}. L_W is a reflection loss factor which allows to characterize the reflection behavior of different materials and N_{min} is the minimum number of reflections a signal is subjected to before arriving at the receiver, which is calculated according to Equation 3.6 with W_{Tx} and W_{Rx} being the street widths of the transmitter and receiver.

$$n_{min} = \left\lfloor 2 * \sqrt{\frac{d_{Tx}d_{Rx}}{W_{Tx}W_{Rx}}} \right\rfloor \tag{3.6}$$

The Corner model assumes a perpendicular grid layout and its range of validity originally ranges from 0.9 GHz up to 2.1 GHz, hence not including the 5.9 GHz inter-vehicle communication band. Besides configuring the distances from the vehicles to the intersection center, solely the street widths and the reflection loss factor can be parametrized. In [GFG+09] the same authors quantify the impact of using a two-ray-ground line-of-sight model compared to the CORNER non line-of-sight model in an urban scenario and found that crucial difference have to be expected. First, the two ray ground model overestimates the connectivity between stations and second, attributed to this, there is a higher interference between transmissions compared to a dedicated urban radio propagation model. Originally only modeling the large-scale path loss as well as impact of shadowing, there exist extensions for the CORNER model to statistically consider the impact of multipath fading by means of Rayleigh and Rician fading, e.g., [MCS+12].

Ray tracing is an approach which employs Maxwell's equations to calculate the paths of a vast number of electromagnetic rays as they disseminate in space, originating from a source. The path of a single ray can be influenced by radio obstacles, due to reflections, diffraction, or scattering along the way and be split up into a multitude of rays. At a receiver these rays interfere with each other by arriving from different angles, at different points in time, but also with different signal strengths. The characteristic of the resulting signal can further change in time as additional waves arrive at the receiver. Ray tracing enables to deterministically model every aspect, from large-scale path loss, over shadow fading, up to multipath fading, but requires detailed 3D scenario descriptions, containing radio obstacles as well as their electromagnetic properties for this purpose. Contrary to the previously presented approach, ray tracing hence enables to model heterogeneous scenarios, not just perpendicular road grids. In several works it has been shown that ray tracing allows for an adequate representation of real channel measurements (e.g., [NAT+13], [Mau05]).

One of the first to employ this modeling approach in an inter-vehicle environment were Maurer et al. ([MSW01], [MFSW04]). The price that one has to pay by employing this fine grained modeling approach is the immense execution time requirement which generally prevents its application for network oriented research, where the primary focus is on interaction between multiple stations/vehicles. Schumacher et al. [SSK09] for instance reported a computing time of $\approx 0.5\,s$ for a reflection order of only two reflections with a ray tracing model which goes up to more than $100\,s$ for a reflection order of five. These times clearly indicate the limited applicability of this approach for network oriented research. Within the electrical engineer domain, however, ray tracing is being employed for research questions within the area of inter-vehicle communication, for instance to determine antenna placements [RMFZ11] or for physical layer simulations [MFW05].

Empirical considerations:

A different modeling approach is pursued by empirical models. The basis are real-world measurements which are used to parametrize a function (regression curve) to best fit with the collected data. The range of validity for such a model consequently comes along with conditions that were included in the data collection, i.e., the degree of vegetation, traffic conditions or frequency ranges.

Log-distance path loss models are often used as a starting point for a to be fitted regression curve. According to Rappaport [Rap01] its generally form can be stated as:

$$\overline{PL}(d) \propto (\frac{d}{d_0})^n \tag{3.7}$$

where $\overline{PL}(d)$ represents the average to be expected path loss at a distance d with d_0

being the reference distance which has to be determined from measurements and n being the path loss exponent, representing the rate at which the path loss increases. For a path loss exponent of two, the attenuation increase is comparable to the free space path loss. In most cases, the formula is nowadays extended to include a statistical modeling of shadow fading effects, resulting in the log-normal shadowing formula:

$$PL(d) = \overline{PL}(d_0) + 10n * log(\frac{d}{d_0}) + X_\sigma \tag{3.8}$$

which denotes the path loss in dB where X_σ is a Gaussian distributed random variable with a mean of zero and a standard deviation of σ. The model can be parametrized and adapted to various environments by appropriately selecting the path loss exponent n, the standard deviation σ, as well as the reference path loss $\overline{PL}(d_0)$.

Within the area of inter-vehicle communication several channel measurements have been conducted and slightly different parameterizations have been derived. Cheng et al. [CHBS08], for instance, conducted measurements in highway as well as rural scenarios at 5.9 GHz and found a best fit using a dual-slope model with a breakpoint distance of $\approx 220\,m$. Dual-slope models basically employ two different path loss exponents (or more general two parametrizations) to characterize the propagation, in combination with a breakpoint distance which determines when to use which path loss exponent (cf. [SAZ07]). For the highway scenario, a path loss exponent of 1.9 and a σ of $2.5\,dB$ for distances up the breakpoint distance and a path loss exponent of 4.0 and a σ of $0.9\,dB$ beyond the breakpoint was found to be the best fit for the collected data. Kunisch et al. [KP08] report a quite similar path loss exponent of 1.85, a σ of $2.3\,dB$ and a reference loss of $59.7\,dB$ at a distance of $1\,m$ for data collected in a highway scenario and a reference loss of $68.7\,dB$, path loss exponent of 1.61, and σ of $3.4\,dB$ for urban scenarios.

Channel measurements with the aim to derive channel models not only for line-of-sight, but as well for non line-of-sight conditions in urban scenarios were conducted, for instance, within the Winner-II project [KMH+07] and by Mangel et al. [MKH11]. These modeling approaches therefore require to be able to distinguish between line-of-sight and non line-of-sight conditions so that the corresponding path loss model can be applied. While for rectangular intersections, this classification can be done quite easily it might pose an additional burden otherwise.

Within the Winner project, which did not focus on characterizing radio propagation conditions in a vehicular environment, but which originated from the mobile communication community with the objective to cover a wide range of environments, several project partners conducted field measurements under various conditions and several model parameterizations were proposed for various fields of applications, ranging from indoor office, over urban and sub-urban, up to rural use. The resulting data per scenario was then used to find a best fit of the following log-distance path loss formula:

$$PL(d) = A * log_{10}(d) + B + C * log_{10}(\frac{f_c}{5.0}) + X_\sigma \tag{3.9}$$

where A represents the path loss exponent, B corresponds to the reference loss, and X_σ is again a Gaussian distributed random variable with zero-mean and a standard deviation of σ. The parameter C is used to describe the path loss frequency dependence with f_c being the center frequency in GHz. Reported valid frequency ranges for the Winner-II models are from $2\,GHz$ to $6\,GHz$.

For use within the context of urban inter-vehicle communication channel modeling the *urban micro cell* scenario is the best fit. In line-of-sight conditions it is suggested to parametrize Equation 3.9 with $A = 22.7$, $B = 41$, $C = 20$, and $\sigma = 4\,dB$ up to a breakpoint distance d_{bp}, which is calculated by:

$$d_{bp} = 4\frac{(h_{Tx} - h_0)(h_{Rx} - h_0)}{\lambda} \tag{3.10}$$

with h_{Tx} being the antenna height of the transmitter, h_{Rx} the antenna height of the receiver, h_0 is called *effective environment height* and reflects the current traffic conditions with valid ranges from 0.5 meter (low traffic) to 1.5 meters (heavy traffic), and λ being the wavelength. Beyond the breakpoint distance it is suggested to utilize a parameterization of $A = 40$, $B = 41 - 17.3 * log(d_{bp})$ (hence incorporating the antenna heights), $C = 20$, and $\sigma = 4\,dB$.

In non line-of-sight conditions, the path loss is calculated as the minimum of $PL_{NLOS}(d_{Tx}, d_{Rx})$ and $PL_{NLOS}(d_{Rx}, d_{Tx})$ with $PL_{NLOS}(d_1, d_2)$ being calculated as:

$$PL_{NLOS}(d_1, d_2) = PL_{LOS}(d_1) + 20 - 12.5 * n_j + 10n_j * log(d_2) + 3 * log(f_c/5.0) \tag{3.11}$$

with PL_{LOS} being the line-of-sight path loss, d_{Tx} the distance from the transmitter to the intersection center and d_{Rx} the distance from the intersection center to the receiver (again under the assumption of a perpendicular intersection layout), f_c being the frequency in gigahertz, and n_j is calculated as:

$$n_j = max(2.8 - 0.0024 * d_1, 1.84) \tag{3.12}$$

Its origin within the cellular community can be seen based on the validity range of the antenna heights, which assumes a communication between a base and mobile station, with antenna heights of $10\,m$ and $1.5\,m$, respectively.

The VirtualSouce11p model [MKH11] is based on measurements which were conducted at several intersections in the city of Munich and which were later again used to find a best fit of a log distance model. Contrary to the Winner-II project, the hereby conducted measurement was focused on urban vehicle-to-vehicle channel conditions, resulting in a used frequency of $5.9\,GHz$ and antennas which were mounted on a vehicle or alternatively on a pole at car roof height ($\approx 1.5\,m$). The model allows to individually adjust the receiver and transmitter street widths in a range from $15\,m$ to $40\,m$. Based on the conducted measurements it is proposed that fading should be modeled by a zero-mean Gaussian distributed random variable with $\sigma = 4.1\,dB$. Based on the fact that the measurements for the VirtualSource11p model solely originated from intersections within Munich, Abbas et al. [ATZ+13] performed a validation of the proposed non line-of-sight model with data collected in the Swedish cities Lund and Malmö and found it to be a proper representation.

The non line-of-sight path loss formula of the VirtualSource11p model is stated in Equation 3.13.

$$PL_{NLOS}(d_{Tx}, d_{Rx}) = 3.75 + i_s 2.94 + \begin{cases} 10log\left(\left(\frac{d_{Tx}^{0.957}}{(x_t w_r)^{0.81}} \frac{4\pi d_{Rx}}{\lambda}\right)^{2.69}\right), d_r \leq d_{bp} \\ 10log\left(\left(\frac{d_{Tx}^{0.957}}{(x_t w_r)^{0.81}} \frac{4\pi d_{Rx}^2}{\lambda d_{bp}}\right)^{2.69}\right), d_r > d_{bp} \end{cases} \tag{3.13}$$

with d_{Tx} and d_{Rx} being again the distances from the intersection center to the transmitter, respectively receiver, λ the wavelength, w_{Rx} the receiver street width, x_t the distance from transmitter to the building wall, d_{bp} the breakpoint distance which is calculated according to Equation 3.10 with $h_0 = 0$, and i_s specifies suburban ($i_s = 1$) or urban ($i_s = 0$) radio conditions.

In addition to previously presented Winner II and VirtualSource11p models (which will later be employed), several other modeling approaches for urban inter-vehicle communication conditions exist which are briefly sketched in the following.

The recommendation ITU-R P.1411-7 [ITU15] proposes further empirical channel models for outdoor short range communication, distinguished in line-of-sight and non line-of-sight models. Sai et al. [SNM+09] propose a model parametrization for urban vehicle-to-vehicle propagation conditions in line-of-sight as well as non line-of-sight which is based on measurements conducted at a frequency of 792.5 MHz in the city of Tokyo. Sommer et al. [SEGD11] further proposes an inexpensive empirical shadowing model which aims to represent the path loss by modeling the additional attenuation of a signal as it penetrates through obstacles, e.g., the exterior wall of a house, and does not consider the impact of propagation paths via reflections. Abbas et al. ([ASKT15], [AKT12]) propose a parametrization for a dual slope log-distance path loss model, separated in line-of-sight and obstructed line-of-sight conditions, which is based on real world measurements. Similarly, Boban et al. [BVF+11] consider the impact of vehicles as obstacles in vehicular communication and propose an approach to distinguish between different line-of-sight conditions and consequently consider additional attenuation due to obstructing vehicles. In [BBT14] this approach is incorporated into a more general modeling framework which separates between i) line-of-sight, ii) non line-of-sight due to obstructing vehicles, and iii) non line-of-sight due to buildings and employs corresponding models for every situation.

A survey on vehicle-to-vehicle propagation channels for different scenarios is given in [MTKM09], while [QNS+15] focuses particularly on giving an overview on different obstacle modeling approaches for inter-vehicle communication conditions.

3.2.2 Applicability of Commonly Employed Models

In this subsection on the one hand commonly employed urban radio propagation models, which are taken up later in the section, are compared to each other with the focus of identifying validity ranges as well as to which extent these models can be parametrized. On the other hand, an overview is given how the validity and applicability of commonly employed simplified radio propagation models has been addressed within related work.

Urban non line-of-sight model comparison

In the following we are focusing on presenting the validity ranges as well as parameterability of three commonly employed urban radio path loss models for VANET simulations which we are going to utilize later on in this chapter. These are the analytical CORNER model [GFPG11] and the two empirical Winner II [KMH$^+$07] and VirtualSource11p [MKH11] models. A common assumption for all three models is the existence of a rectangular intersection with a layout similar to the one visualized in Figure 3.1. The distance between transmitter Tx and receiver Rx is hereby the combined distance between transmitter and intersection center (d_{Tx}) and intersection center and receiver (d_{Rx}). Receivers on the same street as the transmitter are assumed to be in line-of-sight, receivers on the rectangular street are in non line-of-sight conditions. However, the VirtualSource11p and CORNER model further employ so called *transition zones* which take into account that in close proximity to the intersection center there are often still line-of-sight conditions.

While the VirtualSource11p and CORNER model further incorporate the street widths w_{Tx} and w_{Rx} into their path loss calculation, the WINNER II model only employs this information for determining the transition from line-of-sight to non line-of-sight conditions. The VirtualSource11p model further allows to position the transmitter at an arbitrary position within the street width (by adjusting X_{Tx}), where the other models assume the transmitter to be positioned in the center of the street. The Winner II model is the only one which allows to configure a so called *effective environment height* which corresponds to the current traffic situation and influences the breakpoint distance (cf. Equation 3.10) which determines which line-of-sight model parametrization is being used. Similarly, for non line-of-sight modeling, the VirtualSource11p model employs a breakpoint distance to distinguish between the range where the radio condition is primarily influenced by reflections or later on by diffractions. The VirtualSource11p and CORNER models do not explicitly model LOS

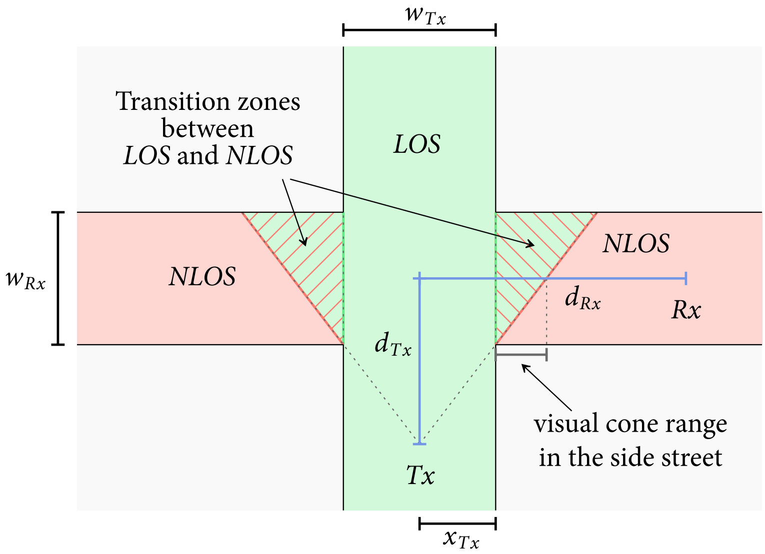

Figure 3.1: Basic rectangular intersection layout which is assumed by commonly employed urban radio propagation models. Figure taken from [Sch13].

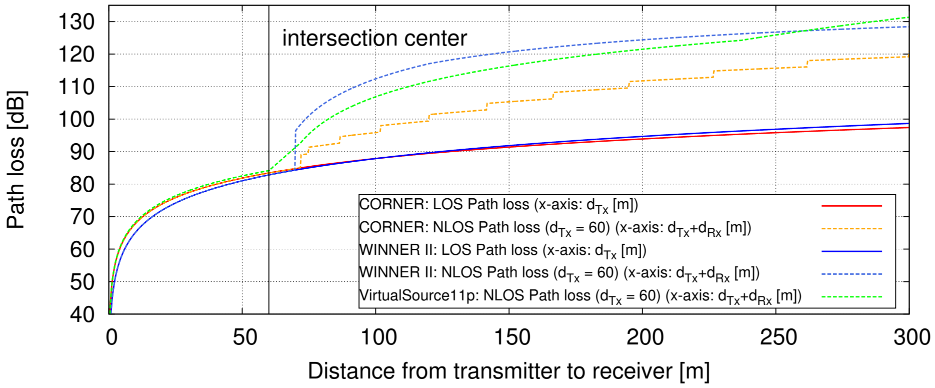

Figure 3.2: Path loss in line-of-sight as well as non line-of-sight conditions as calculated by the *CORNER*, *Winner II*, and *VirtualSource11p* urban propagation models.

conditions, whereby the later suggest to use the free space path loss model. Based on its analytical approach, the CORNER model further allows to configure the reflection loss factor, which is per default set to $-2\,dB$.

Within the context of modeling urban vehicle-to-vehicle radio propagation conditions, the biggest concerns for employing these models are the validity of i) the WINNER II model with respect to the limitation of the transmitter antenna height (5 m to 20 m), and ii) the CORNER model with respect to the underlying radio frequency of 900 MHz to 2.1 GHz, whereby a frequency of 2.4 GHz (IEEE 802.11b/g) was used for the validation.

Figure 3.2 gives a basic overview over the path loss estimations of previously discussed urban radio propagation models. The distance from transmitter to intersection center (d_{Tx}) is assumed to be 60 meters, the street width 20 meters, the transmitter is located in the center of the street and for the Winner II model the transmitter antenna height is set to five meters. All other parameters are set to their default values. As expected, no severe difference for line-of-sight conditions can be seen. Under non line-of-sight conditions the differences generally increase.

In case of the CORNER model a staircase-shaped increase can be seen, which is due to the analytical model calculating the number of occurred reflections between transmitter and receiver and multiplying this value with the reflection loss factor. Depending on the electromagnetic properties of the surrounding, the reflection loss factor can and should accordingly be adjusted. The path loss increase for the two empirical models is more regular with the Winner II model predicting a more severe increase at close range to the intersection. At further distances, the breakpoint distance for the VirtualSource11p model is exceeded, resulting in a more severe increase from this point on. Differences at close proximity to the intersection center are due to different ways of handling the transition zone (cf. Figure 3.1). For instance, while the Winner II model assumes a hard transition to non line-of-sight conditions at distances larger than the half road width, the VirtualSource11p model suggests to use a smoother transition approach, which is realized as a linear LOS-NLOS transition in this case.

Table 3.1 gives an overview of the parameterability as well as validity of previously discussed non line-of-sight urban radio propagation models.

	Parameterability and stated validity						
Model	Purpose	Frequency	Antenna heights	Street widths	Position on street	Street topology	Environmental considerations
Corner [GFPG11]	LOS and NLOS	0.9, 1.5, 2.1 GHz (2.4 GHz for validation)	n.a.	$> 10\ m$	assumption: centered	rectangular	reflection loss adjustable
Winner II[a] [KMH+07]	LOS and NLOS	2-6 GHz	tx: 5-20 m, rx: 1.5-20 m	validity: $> 7\ m$, assumption: 20 m	n.a.	rectangular	effective environmental height[b]
VSource11p [MKH11]	NLOS	5.9 GHz	1.5 m	15-40 m	offset tx to wall	rectangular	distinction: urban/suburban[c]
Ray tracing [Mau05]	any	any	any	any	any	any	any
ITU-R 1411-8 [ITU15]	LOS and NLOS	general: 0.3-100 GHz, 0.8-16 GHz(NLOS)	tx: 4-50 m, rx: 1-3 m (according to earlier version)	receiver street width $< 10\ m$ for NLOS	n.a.	adjustable corner angle for NLOS	effective road height[d]
Sai [SNM+09]	LOS and NLOS	0.8 GHz	adjustable, validation: 1.8-5 m	adjustable	n.a.	rectangular	-

Table 3.1: An overview and comparison of urban non line-of-sight radio propagation models

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[a] Winner II specifies a total of 17 propagation scenarios, with the *urban micro-cell scenario B1* being the best match for inter-vehicle communication conditions

[b] Representing the traffic level within the scenario. In urban scenarios it is generally assumed to be 1.0 meters, but can be adjusted from 0.5 m to 1.5 m. On the one hand the effective environmental height h_0 influences the breakpoint distance d_{bp} (cf. Equation 3.10), which determines which model realization of the dual-slope LOS model is being employed and on the other hand it also directly influences the path loss for distances larger than the breakpoint distance in LOS and NLOS

[c] In suburban scenarios the model assumes an additional path loss of 2.94 dB

[d] The effective road height is basically similar to the effective environmental height of the Winner II model. It allows to distinguish between light and heavy traffic conditions and directly influences the path loss as well as breakpoint distance

Model validation approaches

In order to verify the validity of existing urban inter-vehicle radio propagation models, real world measurements are commonly considered as a data foundation. In case of previously discussed empirical models, this process hereby implicitly comes along with the applicability and generalizability of the data which has been utilized for model building. In case of analytical models, for instance the CORNER model [GFPG11], a model validation is commonly done afterwards by means of a measurement campaign. Another general approach is to compare key characteristics of the modeled wireless channel with that of real channel measurements (cf. [MMK+11], [WCL09]).

Based on its deterministic nature in combination with accurate and fine-grained channel modeling abilities, ray tracing has also been employed for assessing a model's validity in the past. In related work there are several papers within the domain of mobile ad hoc networks ([MKK07], [SW06], [SR08]) which employ ray tracing within an urban scenario and conclude that significant differences have to be expected, compared to the pure free space or two-ray-ground model. However, a comparison to non line-of-sight approaches is not done.

3.2.3 Conclusion

As the previous two subsections indicated, there are a variety of different approaches which are employed for modeling urban radio propagation conditions. Within the vehicular community, there is basically the consensus that, on the one hand, ray tracing allows for an accurate consideration of influencing factors, yet it is computational too expensive for network oriented research, which is why approaches are explored to simplify the complex calculation ([LBP+12], [PFS11]) or speed up the calculation by acceleration techniques, such as GPU support (e.g., [KS10]). On the other hand, simplified models, which are commonly employed nowadays, have been shown to not be able to capture decisive characteristics, such as vehicles obstructing the line-of-sight path ([AKT12], [BBT14]) or the street layout [GSB12]. Consequently, several model extensions have been proposed, with some of them having been presented in previous subsections, which, however, incorporate only one additional aspect at a time. The range of available radio propagation models hence increases steadily, with every single one of them having a dedicated use case, but increasing uncertainty when to employ which model.

In this work, we pursue a different approach, by not offering yet another model, but by revealing differences which have to be expected by employing different model realizations. For this reason, we take a first step in evaluating which aspects influence radio conditions in urban areas to which degree and how these individual aspects affect each other. We consequently consolidate existing works and evaluate in which situations a more detailed radio propagation modeling might yield substantially different results with respect to the requirements of IEEE 802.11p networks. These insights hence directly address the raised research question of whether *the abstraction level of commonly employed urban radio propagation models is appropriate for network oriented research*. With respect to dependability assessment of inter-vehicle communication networks, our results give an overview of what the situations are that might be most challenging for future urban vehicle-to-vehicle applications and which thus might have to be considered separately, e.g., by performing field trials under such conditions.

Ray tracing is therefore chosen as the evaluation methodology of our choice, since it has been shown to adequately represent real channel measurements (e.g.[Mau05], [NAT+13]) and its analytical nature ensures consistency while investigating the impact of certain aspects. While the validity of currently employed analytical and statistical urban radio propagation models is generally limited to perpendicular intersection layouts with homogeneous conditions, ray tracing allows for a modeling of heterogeneous conditions. In the following, we will first present how ray tracing can be employed for a fine grained modeling of urban radio propagation conditions and a sensitivity analysis is being performed, highlighting severe radio conditions. Finally, we compare the achieved results by means of ray tracing with that of commonly employed radio propagation models by the VANET community and reveal in which situations these models are appropriate. Our assessment is thereby focused on a network perspective, with respect to the requirements and capabilities of IEEE 802.11p with a QPSK modulation scheme, a data rate of 6 Mbps, and OFDM multiplexing.

3.3 Ray Tracing: A Deterministic Radio Propagation Modeling Approach

In this section, first a brief introduction to the basic principles of ray tracing is given, before we discuss challenges that come along with employing ray tracing techniques for network oriented research. Subsequently, results from our conducted sensitivity analysis are discussed, which highlight potentially severe radio situations, w.r.t. dependability assessment, and at the same time provide a basis for identifying key characteristics of urban radio propagation. In the next section these insights are then employed to assess whether the identified key characteristics are appropriately represented by commonly employed urban radio propagation models.

3.3.1 Principles of Ray Tracing

Ray tracing has two fundamental differences compared to previously presented simplified models in Section 3.2.1. On the one hand, a raytracer considers the propagation of several rays from a transmitter to a receiver in order to determine the path loss. These individual rays can all take different paths, be reflected, diffracted, or scattered at different objects, but still collectively contribute to the signal strength at the receiver. Individual rays can thereby interfere constructively, i.e., increase the signal strength, or be destructive, depending on the phase difference between them. None, or only a slight difference in phases is thereby constructive, a difference close to 180° leads to destructive interference. The phase of each wave can generally be determined, based on the propagation distance, the wavelength and potential phase shifts due to, e.g., reflections. Consequently, this enables to consider the impact of multipath

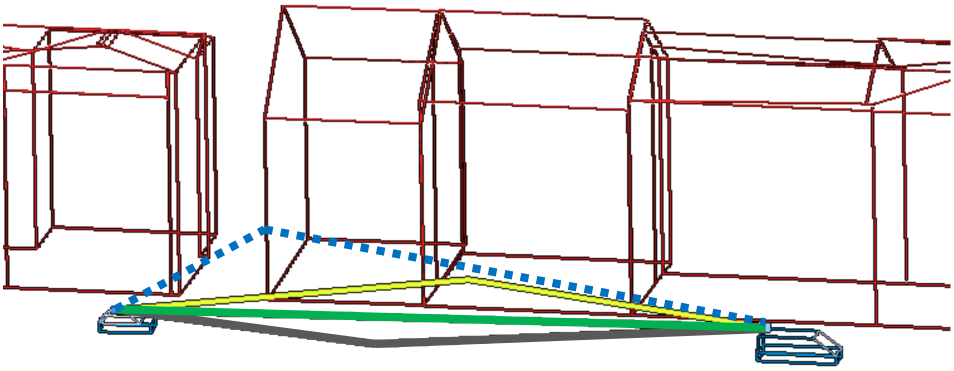

Figure 3.3: Microscopic view on four exemplary propagation paths between a transmitting and receiving vehicle in direct line-of-sight without considering any radio obstructions, except for the house facades. The green path is the line-of-sight and consequently strongest path. Furthermore, two additional reflection paths are visualized. The gray one reflects on the ground, the yellow one at the facade. The dotted blue path is one out of many scattered paths. Figure first published in [GH14].

propagation, by *adding* up the signal strength of several hundreds or thousands of rays with respect to their phases at the receiver.

On the other hand, ray tracing enables to consider scenario specific properties, such as varying street widths, non constructed areas, curved streets, or the presence of individual objects, implicitly incorporating shadow fading effects. Considering this wide range of influencing effects requires detailed scenario descriptions, including the position and shape of objects, as well as their electromagnetic properties. As a consequence, this approach is computational expensive – taking several seconds per transmitter-receiver combination and another several minutes of pre-processing for every transmitter position. For a more extended introduction in ray tracing and a description of the employed ray tracing model we refer to [Mau05].

Raytracer settings: Without any further limitations a raytracer determines a vast amount of possible propagation paths for a transmitter receiver constellation, resulting in an enormous execution time, with most of the considered paths having neglectable influence in the end. For this reason one generally limits, e.g., the amount of interactions considered or only progresses paths whose path loss do not exceed the current best path plus some threshold. For our settings we configured this threshold to be 50 dB and considered paths with up to 8 interactions, whereby a maximum of 2 diffractions are considered. As a center frequency we used 5.9 Ghz, resulting in a wavelength of approx. 5.08 cm. In the following let us now consider one exemplary situation and microscopically go through it to i) better understand the mechanics of a raytracer and possible influences of multipath propagation and ii) justify the previously mentioned raytracer settings.

Exemplary scenario: Figure 3.3 visualizes a simple scenario with a transmitter and receiver in direct line-of-sight. In total four different paths are visualized, being explained in the caption in more detail. For a distance of 80 meters between the trans-

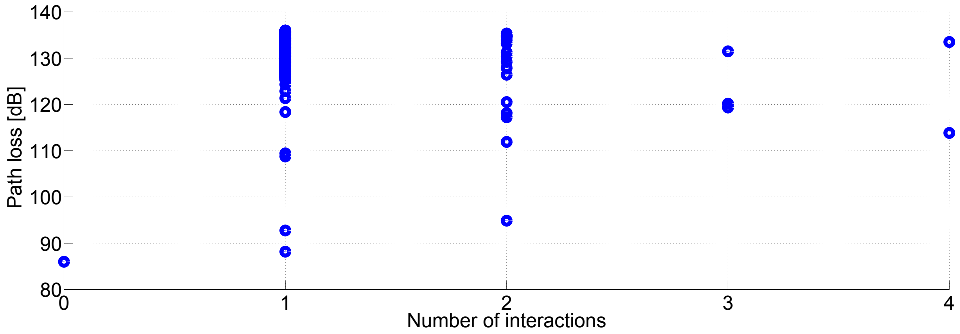

Figure 3.4: Scatterplot, visualizing the path loss of every ray arriving at an exemplary receiver with a distance of 80 meters to the transmitter, separated by the number of interactions (reflections, diffractions or scattering) along the path. In total 683 path losses are visualized. Figure first published in [GH14].

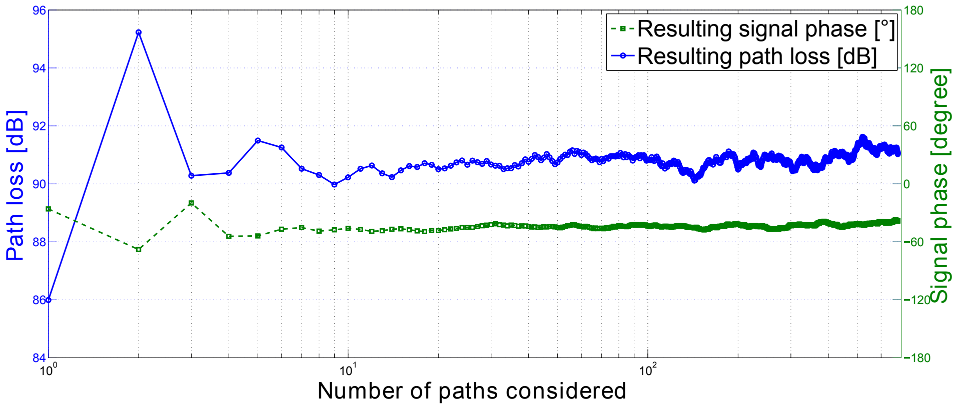

Figure 3.5: Impact of the number of considered paths on the overall path loss and phase of the signal. The individual path loss values are visualized in Figure 3.4 and are considered in ascending order for determining the overall path loss, i.e., the strongest paths are "added" first. The x-axis is in logarithmic scale. Figure first published in [GH14].

mitter and receiver we obtain 683 paths whose individual path losses are visualized in Figure 3.4, separated by the number of interactions along the way. The line-of-sight path is obviously the strongest one with a path loss of approx. 86 dB. The second strongest path is the ground reflection path (gray one in Figure 3.3) with a path loss of approx. 88 dB, the third one a reflection path at the house facade with a path loss of approx. 93 dB. It becomes obvious that there are only a few paths with a resulting path loss in the range of the strong line-of-sight path in this scenario, whose impact on the overall path loss is considered next. For the sake of completeness it is noted that there are a total of 662 paths with one interaction considered, 16 paths with two interactions, three paths with three interactions, and two paths with four interactions.

Figure 3.5 visualizes the resulting overall path loss in combination with the phase of the signal, depending on how many paths are considered. The first path loss and phase thereby corresponds to the values of the strongest path (line-of-sight path), additional paths are considered in ascending path loss order. Solely considering the line-of-sight path results in a path loss of 86 dB, which corresponds to the free space path loss at a distance of 80 m. Additionally considering the ground reflection path, with a path loss of 88 dB (cf. Figure 3.4), results in an increase of the overall path loss to 95 dB, due to destructive interference. The reason therefore is an extended propagation path by an integral multiple of the wavelength ($\lambda \approx 5.08\,cm$) compared to the line-of-sight path in combination with one reflection on the ground, which leads to a phase shift of ≈ 180° (due to a higher index of refraction). This value hereby corresponds pretty well with the estimation of the two ray interference model [SJD12], which particularly represents the line-of-sight as well as the ground reflection path. Considering also the third strongest path (reflecting from the house facade), with a path loss of 93 dB, has a constructive effect, resulting in an overall path loss of 90 dB. Further consideration of additional paths only marginally influence the overall path loss in this scenario, as can be seen in Figure 3.5. For completeness the phase of the signal is visualized as well, which stays rather constant after only several paths in the considered scenario. Under consideration of the QPSK modulation scheme, which does not incorporate the amplitude and is rather robust against phase shifts of $< 45°$, these variations do not pose any difficulty for the decoding of the transmitted data symbol. Summarizing the results of Figure 3.5 and already anticipating some insights, it can be seen that for a situation with destructive interference the consideration of only one path is too optimistic (free space path loss model), while considering two paths (two ray interference model) can result in too pessimistic estimations in urban conditions, since additional constructive propagation paths might exist.

3.3.2 Employing Ray Tracing for Network Oriented Research

The cost that one pays for being able to accurately model heterogeneous scenarios is the immense execution time requirement of this approach. The employed three-dimensional ray tracing model [Mau05] is based on the so called *mirroring method* which gradually follows reflection paths up to a maximum number of interactions per path between transmitter and receiver. The resulting complexity can hereby be stated as

$$O(k^n) \text{ with } k \gg n \qquad (3.14)$$

with k being the number of polygons in the considered scenario and n the maximum allowed reflection order [Mau05]. Quite obviously, an immense execution time increase has to be expected for an increase in the reflection order. An applied optimization technique is to reduce the complexity by only considering polygons which are visible at first hand. Within a pre-processing step, which is executed once per transmitter position, the employed ray tracing model performs such an optimization and further pre-calculates diffraction edges. As part of a diploma thesis [Sch13], we measured the time requirement of this optimization step on an Intel®Xeon®E5-2670 CPU running at 2.6 GHz and a scenario, consisting of 4 116 objects formed by 28 650 polygons, representing about two square kilometers of inner city scenario in

Karlsruhe, Germany. An extract, visualizing the modeled granularity is shown in Figure 3.6. Calculating the diffraction edges is in the order of half a minute, another half a minute is used for optimizing the representation of object data and calculating the visible polygons takes in between 5 and 105 additional minutes, depending on the maximum interaction depth. The overall resulting preprocessing time which is required once per transmitter position is listed in the second column of Table 3.2.

The execution time to calculate possible paths for a transmitter receiver constellation depends again on the number of maximum considered interactions as well as on the exact positions of transmitter and receiver. Within the same diploma thesis, we measured the required execution time for a separation distance of 150 m at an intersection under non line-of-sight conditions. While for a maximum interaction depth of three, the calculation of all possible paths (which can then be used in a post processing to determine the path loss, frequency shift, or delay spread of the signal) took approximately 6 seconds, it increased to $\approx 60\,s$ for a maximum interaction depth of six (cf. Table 3.2). Obviously, the resulting execution times prohibit the use of this fine grained ray tracing approach during simulation runtime.

One possibility which we proposed in [GRM+12] and which has been previously employed in a slightly different context (e.g., [SB07], [SK06]) to nevertheless employ execution time expensive ray tracing is to make use of a pre-calculation scheme. The general idea is to pre-calculate a *radio map*, based on possible transmitter/receiver-constellations which can then be used by network simulators by means of a simple table lookup. However, such a pre-calculation approach possesses inherent limitations, such as for instance not being able to depict any dynamic during runtime. Within the vehicular domain this restriction is most obvious with respect to driving vehicles which are on the one hand potential transmitters and receivers themselves, but at the same time radio obstacles for other ongoing communication. While in traditional mobile networks a consideration of mobility traces might do the trick, it is of no use for most VANET related research, since received information might change the driving behavior and hence the trajectory and position of vehicles during runtime. Since consequently exact positions cannot be known beforehand, a certain spatial

Maximum interaction depth	Preprocessing	Processing time for one transmitter receiver constellation
3	6 minutes	≈6 seconds
4	18.5 minutes	≈12 seconds
5	43 minutes	≈20 seconds
6	106 minutes	≈60 seconds

Table 3.2: Measured runtimes when employing the ray tracing model in the considered scenario which consists of 4 116 objects formed by 28 650 polygons and covers an area of approximately two square kilometers in the city of Karlsruhe. The preprocessing times (which only have to be calculated once per transmitter position) as well as the processing time for determining possible paths for one transmitter receiver constellation heavily depend on the maximum interaction depth.

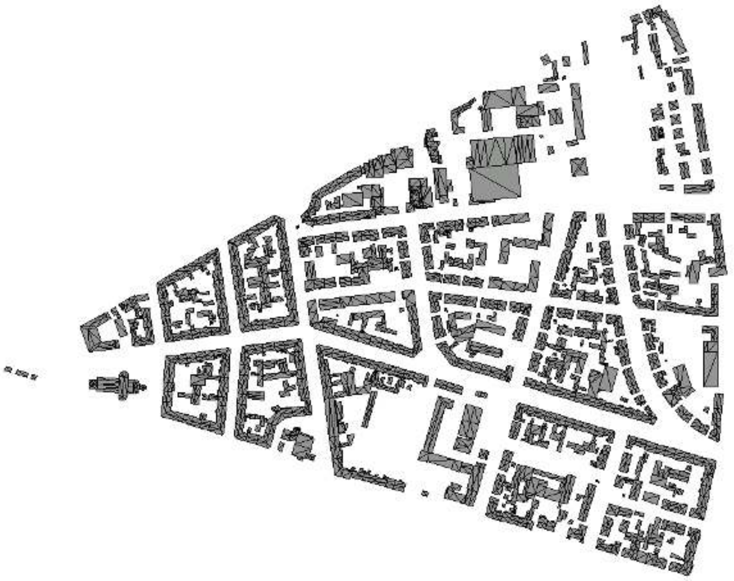

Figure 3.6: Extract of the considered ray tracing scenario, visualizing the considered building granularity and representing an inner city area in Karlsruhe, Germany. The data was provided and is copyrighted by the real estate office of the City of Karlsruhe.

resolution is necessary to limit the number of possible transmitter/receiver-pairs. Hence, there is a tradeoff between pre-calculation time, increasing quadratic with the number of considered positions, and inaccuracies, since arbitrary path loss enquiries have to be mapped to known constellations.

For the scenario, visualized in Figure 3.6 a rough estimation results in about 20 km of roads (counter per lane) and hence in about 10 000 transmitter/receiver positions with a selected resolution of two meters. Under the assumption of bidirectional communication behavior this results in a number of transmitter/receiver-pairs in the order of 50 millions which is by no means manageable, considering previous measured execution times. Hence, additional optimizations are inevitable to further reduce the number of transmitter/ receiver-pairs, with two of them being briefly sketched in the following. One option is to reduce the resolution, resulting in a coarser *radio map* and hence inaccuracies, particularly with respect to the consideration of multipath fading, but also for shadow fading. The usage of interpolation methods is hereby only partly helpful. Another optimization is to eliminate receiver positions which are impossible, or at least highly unlikely, to emerge as “successful” receiver positions by means of fast to calculate heuristics.

To summarize, while the presented approach of pre-processing a *radio map* enables the use of fine-grained ray tracing model output for network simulation, its excessive advance processing time as well as inherent limitations still prevent its employment in most cases. In the following, we hence do not employ ray tracing as direct input for network simulations, but use its insights to perform a sensitivity analysis on existing radio conditions at first, and evaluate the applicability of simplified radio propagation models to represent these situations subsequently.

3.3.3 Sensitivity Analysis of Urban Radio Propagation Conditions

In this subsection, first an overview over the considered scenario is given and the variations are presented which are employed to determine the impact of several radio obstacles as well as varying shapes. Then, the evaluation methodology is presented, before the results are visualized and discussed.

Evaluation scenarios

Our scenario under consideration is depicted in Figure 3.7. It represents an urban intersection scenario in Karlsruhe, Germany [2] with four legs, several parked vehicles, vegetation, traffic signs, post boxes, and traffic on the road. In exactly this scenario the employed ray tracing model was validated by a measurement campaign [Mau05].

In order to determine the impact of the existence of several radio obstacles as well as varying shapes, we considered the following scenarios and variations:

- **Base scenario:** In this scenario only the buildings, as depicted in Figure 3.7, are modeled (including pitch of the roof, bay, or similar). However, no vegetation or vehicles are present. The following scenarios are all based on this scenario, but additionally add further radio obstacles.
    1. **Diverse objects scenario:** This scenario adds vegetation (green objects in Figure 3.7), postboxes, or traffic signs (yellow objects) to it.
    2. **Parking vehicles scenario:** This scenario adds parking vehicles standing at the roadside.
    3. **Traffic scenario:** This scenario adds driving vehicles, located in the center of the road with a height which is below the height of the transmitting and receiving antenna.
    4. **Traffic scenario with obstructed LOS:** In this scenario the *traffic scenario* is altered in a way that the height of several vehicles is increased, resulting in an obstructed line of sight (OLOS) path for vehicles located more than 10 meters away from the transmitter.
- **Complete scenario:** This scenario combines the previous scenarios, by including diverse objects, parking vehicles and vehicles on the road. The resulting scenario is visualized in Figure 3.7. For this scenario we again separated between line-of-sight and obstructed line-of-sight conditions.
- **Scenario shape:** The following scenarios are all based on the *complete scenario*, but obstruct different roads with an additional building to further consider the effect of the shape of an intersection. The resulting four different scenarios are visualized in Figure 3.8 with the added building being highlighted.

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[2] `https://www.google.com/maps/@49.0098514,8.4294506,19z`

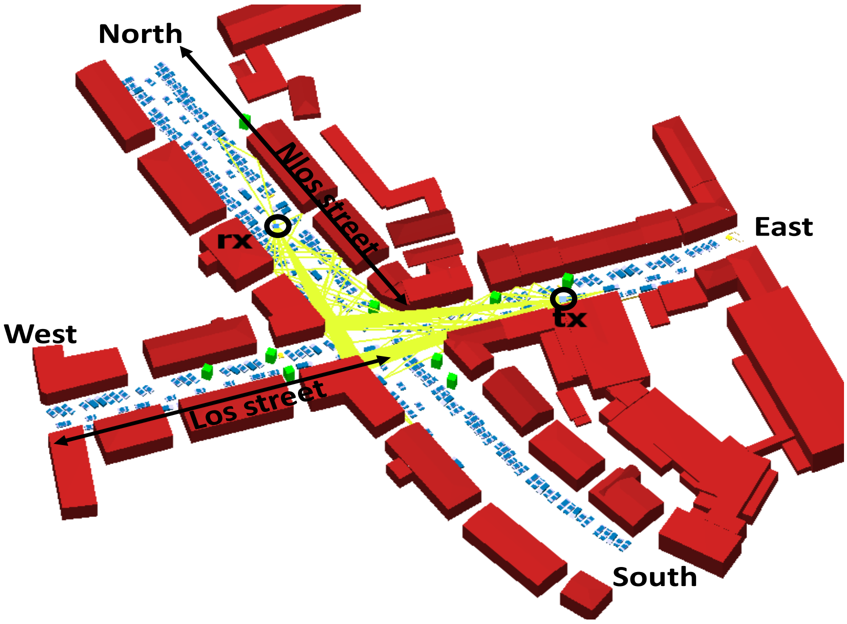
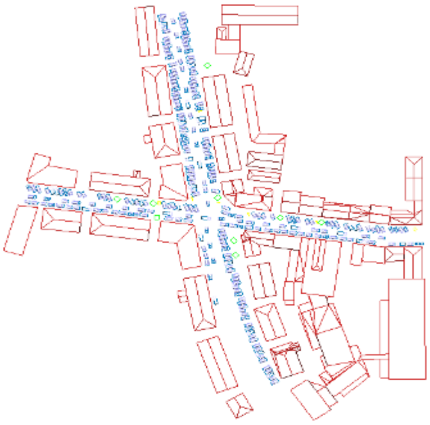


Figure 3.7: Overview of the considered urban scenario, which is a replication of an intersection in Karlsruhe. Transmitter (tx) is exemplarily located 60 meters away from the intersection center. Several propagation paths to a potential receiver (rx) are depicted. Figure first published in [GH14].

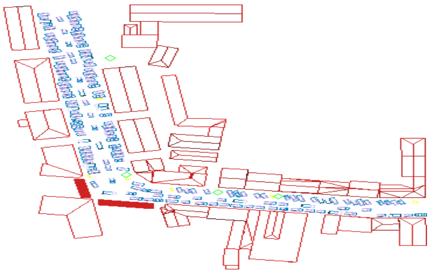
1. **T-crossing scenario:** In this scenario the south road is closed.
2. **L-crossing scenario:** In this scenario, the south road, as well as the west road is closed.
3. **Canyoning scenario:** In the canyoning scenario, the north and south roads are closed.

Evaluation methodology

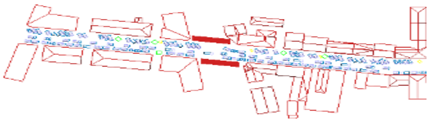
In total we considered three different transmitter positions (30 m, 60 m, and 90 m from the intersection center, whereby in the following only results for 60 m are presented) and evaluated the path loss every 0.25 meters in the direction of traffic, but also lateral to it, in order to cover a wide range of possible outcomes. Such a fine grained sampling is necessary, since interference, due to multipath propagation can have an impact, even within these short distances. Then, in a next step we post-process these samples, by averaging over every lateral position and with a granularity of 2.5 m in driving direction so that the results can be reasonably visualized. Furthermore, the standard deviation is calculated which thus still gives at least an impression of how the fine grained path loss values spread around the calculated average. The results depicted as line-of-sight (LOS) conditions originate from the street heading westwards, while non line-of-sight (NLOS) result were collected northwards. It should be noted, that approx. the first 20 m on the non line-of-sight street (originating from the intersection center) are still within line-of-sight of the transmitter.



(a) Complete scenario



(c) L-crossing scenario



(b) Canyoning scenario

(d) T-crossing scenario

Figure 3.8: Visualization of the four scenarios which were considered for evaluating to which degree the shape of an intersection influences its radio propagation characteristic. The scenarios (b), (c), and (d) are based on the *complete scenario (a)*, but additional radio obstructions (which are highlighted in the figures) are present.

Results and insights

The presentation of the results is divided into three sections. First, results for the base scenario are presented, then the impact of the presence of obstructions is visualized and subsequently we consider the impact of the shape of an intersection on the path loss.

Base scenario:

In Figure 3.9 the path loss for the *base scenario* is visualized, separated in line-of-sight and non line-of-sight conditions. In comparison, the path loss according to the Friis free space formula is visualized. When comparing the line-of-sight path loss, as calculated by the raytracer, with the path loss according to the free-space formula the impact of considering fading conditions, particularly the influence of constructive and destructive multipath interference becomes visible. There are ranges where the path loss, as calculated by the raytracer, exceeds or falls short of the free-space path loss value. This can in particular be seen at the distances of $\approx 20\ m$ and $100\ m$, where destructive interference leads to an increase in path loss within these ranges.

Model sensitivity and impact of fading: In order to depict the differences, due to multipath fading, in more detail as well as to explore the sensitivity of the ray tracing model, we varied the number of maximum considered interactions in the following. The Friis free space path loss model is hereby considered as reference, and we plot the deviation by considering additional paths up to a maximum number of interactions along the way in Figure 3.10. For comparison reason, we additionally visualize the

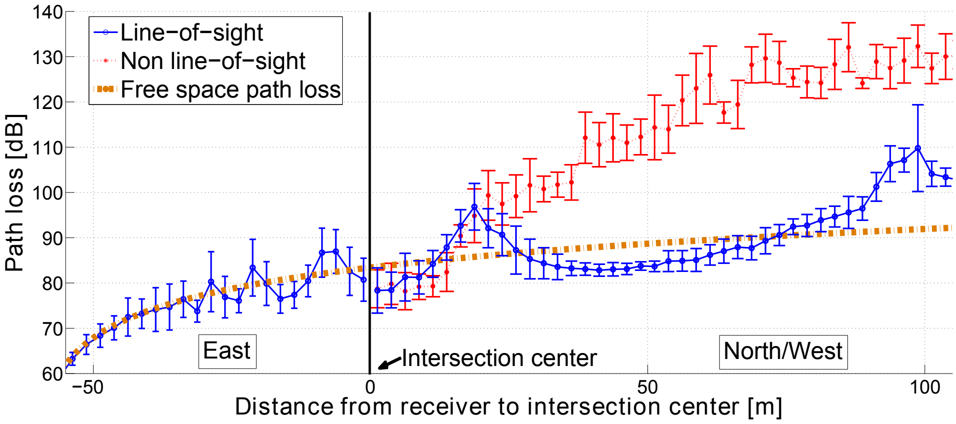


Figure 3.9: Path loss for the base scenario with a receiver located x meters away from the intersection center. The transmitter is located 60 meters away from the intersection center (compare Figure 3.7). Line-of-sight values are collected on the westward road, while non line-of-sight values are collected northwards. Figure first published in [GH14].

previously mentioned analytical two ray interference model [SJD12], which solely models the line-of-sight path as well as the ground reflection path. It can be seen that

- there is only a minor difference in ray tracing if a reduced number of interactions is considered. This observed deviation thereby increases with an increase of distance
- the impact of multipath fading is clearly visible, resulting in areas of destructive and constructive interference. The free space path loss model, which solely models the line-of-sight path, obviously fails to capture these effects
- the ground reflection two ray model, which models the line-of-sight as well as one ground reflection path occasionally overestimates the path loss in urban conditions, compared to considering multiple propagation paths. This is coherent with the insight in Section 3.3.1 and reasoned by the fact that in urban conditions several more strong reflection paths exists, contrary to rural scenarios for which this model is intended for.

The overall deviation, averaging over the complete range, however, is rather small with a difference of only 1.2 dB between fine grained ray tracing and the simple free space path loss model. For our next analysis, we slightly modified the base scenario by varying the antenna heights of the transmitter and receiver, in order to quantify how sensitive the path loss behaves to minor changes of the input, w.r.t. to non radio obstacles. Figure 3.11 depicts that i) the antenna height itself already has a tremendous impact on the specific path loss at a certain position and ii) that distances where one antenna height results in high path loss due to destructive interference might be a distance with constructive interference for another height. This insight, in combination with the low overall absolute deviation, depicts that in case not every

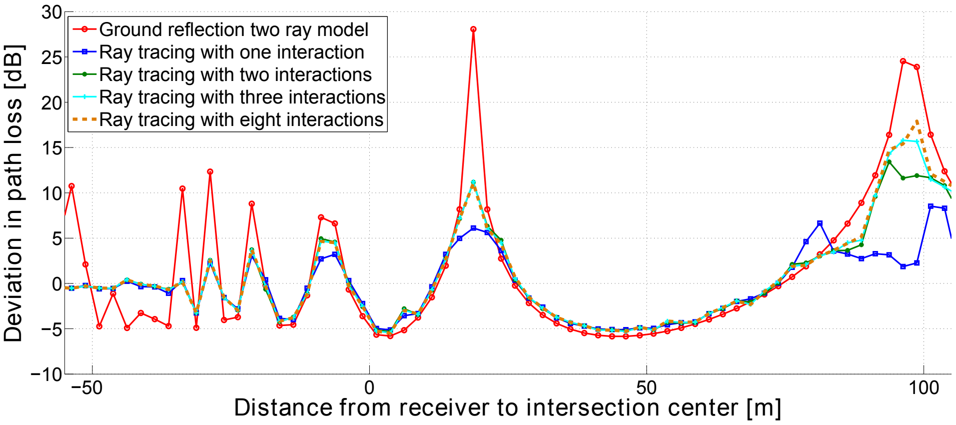


Figure 3.10: Deviation in path loss of different modeling approaches compared to free space path loss for vehicles in line-of-sight condition. Positive values represent a higher estimated path loss compared to the free space model. Figure first published in [GH14].

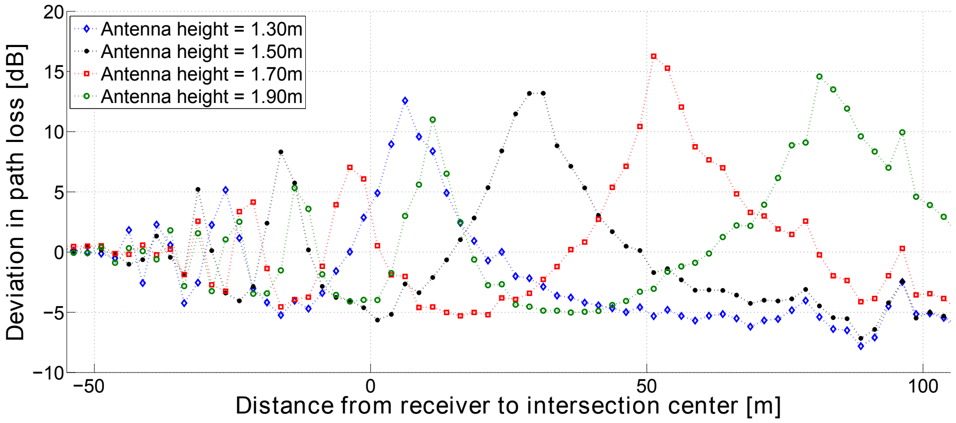


Figure 3.11: Deviation in path loss for different antenna heights, calculated by fine grained ray tracing and compared to free space path loss model for vehicles in line-of-sight condition. Positive values represent a higher estimated path loss compared to the free space model. Figure first published in [GH14].

input parameter is known precisely the free space path loss model provides appropriate average estimations even in urban environments (under line-of-sight conditions).

While we did a similar evaluation for non line-of-sight conditions as well, its results are not visualized, but only briefly sketched in the following:

The path loss on the non line-of-sight road increases more drastically, since there is no longer a strong line-of-sight path, but only several reflected and diffracted rays which arrive at the receiver. Here again, these individual rays interfere with each other, but contrary to the line-of-sight case there are now in general more equally strong paths involved, resulting in less correlation observable. Limiting the amount of considered interactions rather leads to an overestimation of the path loss, since especially under non line-of-sight conditions occasionally still rather strong paths exist with several reflections. A comparison to currently employed non line-of-sight path loss models is shown later on in Figure 3.16.

Presence of obstructions:

The focus of our next evaluation is to quantify the impact of the existence of different radio obstacles, such as vegetation, street signs or vehicles on the path loss in order to get a better understanding of the radio obstacles which are most determining. Figure 3.12 visualizes the path loss under line-of-sight or obstructed line-of-sight conditions, from the transmitter to the intersection center (-60 m to 0 m) and further towards the west (0 m to 110 m). It can be seen that

- the existence of vegetation or street signs does on average hardly have any visible impact
- the presence of parked vehicles rather reduces the path loss in certain ranges. In particular, the largest differences are observable in the ranges where destructive interference led to an increase of path loss in the *base scenario*. The presence of vehicles thereby contribute to multiple strong diffuse paths, mitigating the effect of only having two strong paths with converse phases
- the existence of vehicles on the road can be beneficial in a similar fashion, as long as the line-of-sight path is not obstructed. The reason for this are several rather strong diffraction paths, originating from vehicles on the road as well as parked vehicles
- vehicles obstructing the line-of-sight path have an obvious negative effect on the resulting path loss. The absolute increase due to obstructed line-of-sight condition comes down to 10 dB on average for distances larger than 50 m in our considered scenario. This is in line with the observations made in [AKT12].

To summarize the previous results: i) the presence of additional obstructions not only mitigates the effect of destructive multipath propagation, but further occasionally enables additional strong propagation paths, reducing the overall path loss ii) in case the line-of-sight path is obstructed, the effect of multipath interference diminishes as well, the overall path loss, however, increases drastically (compare red vs. black curve in Figure 3.12).

Figure 3.13 depicts the impact of the existence of various obstructions for non line-of-sight conditions. Contrary to Figure 3.12 no clear trend is observable. Each and every additional radio obstacle can either lead to an increase of the path loss by obstructing otherwise strong propagation paths or result in a reduction of the path loss by offering new strong propagation paths. The deviations in path loss between the individual scenarios is in the range of $\approx 10\ dB$. The path loss value of $110\ dB$ is highlighted, since with a transmission power of $20\ dBm$ (EIRP) and a carrier sense/decoding threshold of $-90\ dBm$ of the receiver, a packet can be detected/decoded up to this range. Comparing the distance up to which a transmission can thus on average be carrier sensed/decoded only yields minor differences in the range of a few meters. However, due to large variations of the path loss within a short distance, occasional receptions might still be possible at larger distances in a given case(cf. std. deviation in Figure 3.9).

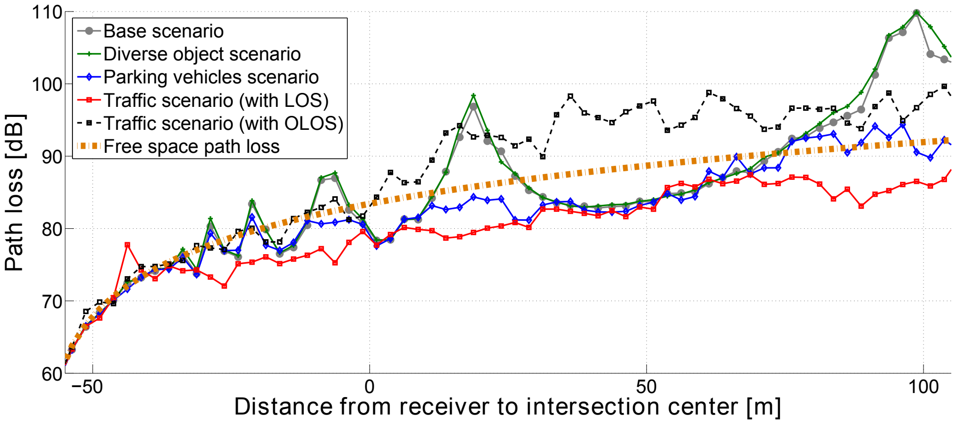


Figure 3.12: Impact of the existence of vegetation, traffic signs, parking vehicles and vehicles on the road on the line-of-sight/obstructed line-of-sight path loss. Figure first published in [GH14].

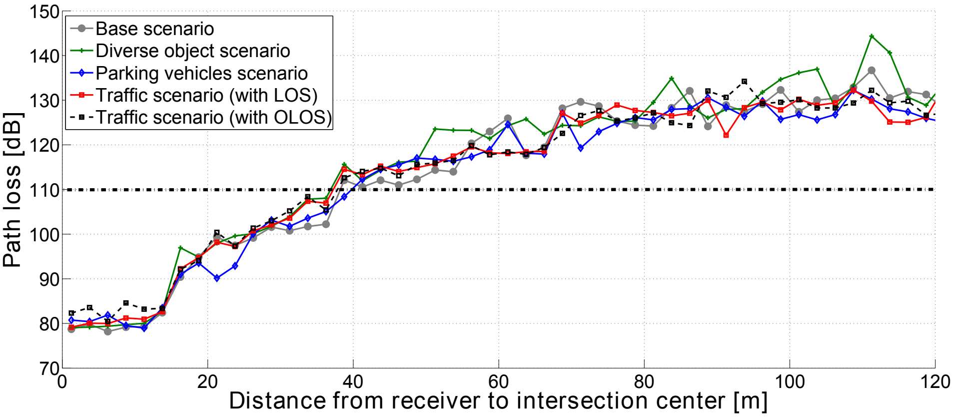


Figure 3.13: Impact of the existence of vegetation, traffic signs, parking vehicles and vehicles on the road on the non line-of-sight path loss. Figure first published in [GH14].

Shape of the scenario:

In the following we consider the impact of the shape of an intersection on the resulting path loss in urban conditions. We therefore consider the *complete scenario* with obstructed line-of-sight as reference and evaluate whether and for which reasons differences in path loss are observable if the scenario layout changes, i.e., we obstruct certain inflows with additional buildings as has been visualized in Figure 3.8. The resulting path loss for obstructed line-of-sight and non line-of-sight conditions (where applicable) for our reference scenario, T- and L-crossing scenarios, as well as the canyoning scenario are presented in Figure 3.14. The first and foremost observation is that there is barely any difference visible when comparing the different shapes. For obstructed line-of-sight conditions a decrease in path loss can be seen at a range from 25 m to 50 m which is due to a strong reflection path at the new inserted building. Similar effects can also be seen under non line-of-sight conditions over a large range. The reason for this is that the newly inserted building occasionally provides additional reflection paths into the side street, which contribute to a stronger signal compared to the predominant diffraction paths.

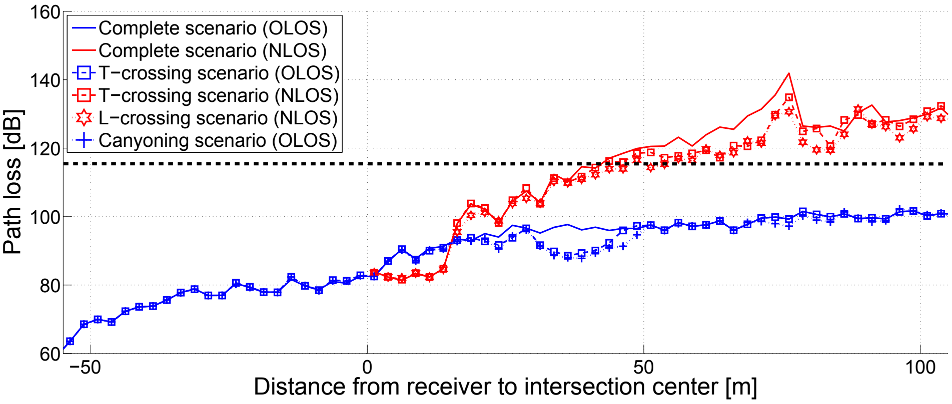


Figure 3.14: Influence of the shape of an intersection on the resulting path loss in obstructed line-of-sight (OLOS), visualized in blue, and non line-of-sight (NLOS) conditions, visualized in red. Figure first published in [GH14].

Conclusion

In this section we evaluated the impact of a deterministic modeling of shadow and multipath fading in a real world urban intersection scenario. By means of ray tracing we identified the situations, i.e., existence of radio obstacles, which are most determining for the overall radio propagation conditions and which thus should be modeled explicitly, even by simplified radio models. Our results indicate that in line-of-sight conditions a difference between various radio obstacle levels is visible, where the obstruction of the direct line-of-sight path has the most detrimental effect. The impact of multipath fading clearly diminishes in a crowded scenario and might thus not have to be modeled explicitly for network oriented research. In non line-of-sight conditions the impact of varying radio obstacles were rather indistinguishable, indicating that its exact characteristic might not have to be modeled explicitly, just as the shape of the scenario which similarly had no major impact.

3.4 Applicability of Urban Radio Propagation Models

In this section, the results of the conducted sensitivity analysis are picked up and we evaluate which situations commonly employed models are able to represent adequately. To achieve this, first, the path loss as calculated by ray tracing for line-of-sight as well as non line-of-sight conditions is individually compared to respective simplified propagation models. Following this, the impact of different model realizations is evaluated by means of networking metrics, such as the packet inter-arrival time or maximum distance at which a first packet reception can take place.

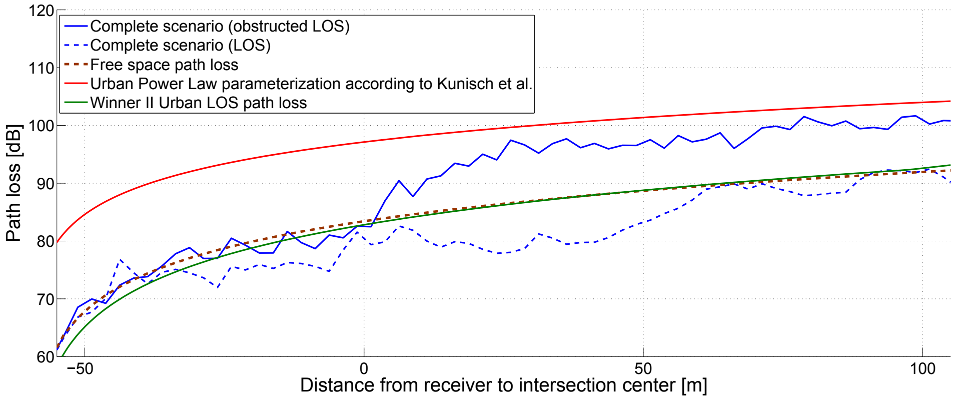


Figure 3.15: Path loss in line-of-sight and obstructed line-of-sight for the complete intersection scenario presented in Section 3.3.3 and as calculated by the ray tracing model, the Friis free space model, Winner II LOS model, and a power law model which has been parametrized according to Kunisch et al. [KP08] for urban scenarios.

3.4.1 Path Loss Comparison

Path loss in line-of-sight conditions

Besides the path loss as calculated by fine grained ray tracing for the complete scenario (cf. scenario description in Section 3.3.3), Figure 3.15 visualizes the path loss estimation of the Friis free space path loss model, the Winner II LOS path loss model and a power law model which has been parametrized according to measurements performed by Kunisch et al. [KP08] in an urban environment. As already previously discussed within the sensitivity analysis, the biggest difference has to be expected in case of an obstructed line-of-sight, which is why the LOS and OLOS path loss as calculated by ray tracing is visualized. It can be seen that the simple Friis free space path loss as well as the Winner II LOS model are rather appropriate representations for pure LOS conditions in an urban environment. Obviously, characteristics, such as constructive interference or strong reflection paths cannot be matched individually, which is why the simplified models pose rather pessimistic estimations. In case of an obstructed line-of-sight path, these two models apparently underestimate the path loss, since there is no longer a strong line-of-sight path available. However, under such conditions the power law model parametrization shows its suitability by implicitly considering these severe conditions. While again, individual outliers cannot be matched, the power law model (parametrized according to Kunisch et al. [KP08]) shows an appropriate trend in representing obstructed line-of-sight path loss behavior for network oriented research.

Path loss in non line-of-sight conditions

Figure 3.16 depicts the non line-of-sight path loss estimation by the ray tracing, Winner II, CORNER, and VirtualSource11p model. For completeness reason, the line-of-sight path loss for the first 60 meters is visualized as well. The three NLOS path loss models have all been configured to best fit the scenario specifics, i.e., street

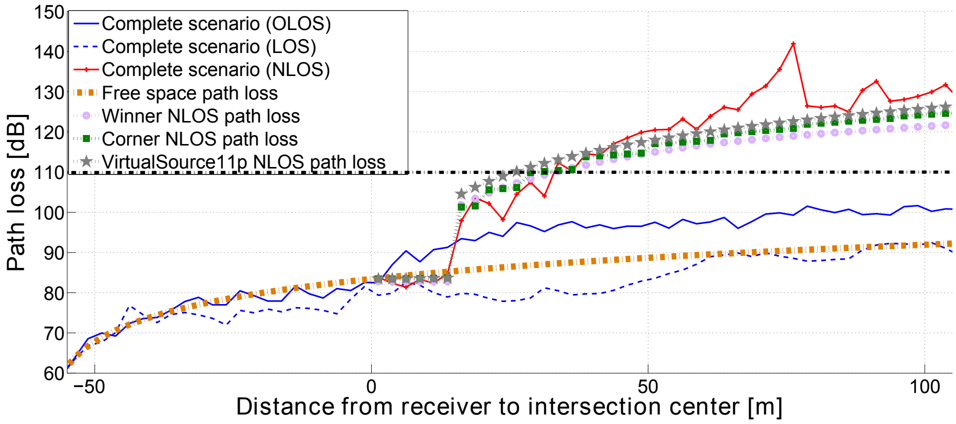


Figure 3.16: Path loss in line-of-sight and non line-of-sight for the complete intersection scenario presented in Section 3.3.3 and as calculated by the ray tracing model, the Winner II, CORNER, and VirtualSource11p path loss models. Figure first published in [GH14].

widths or the path loss factor have been adjusted accordingly. Within the relevant range, i.e., the range at which there is a realistic chance of successful packet receptions, there are no fundamental differences observable between the three simplified path loss models. For instance, there is only a difference of $\approx 10\,m$ when comparing the distance at which the calculated path loss exceeds the carrier sensing range. Similar to line-of-sight conditions, individual outliers as calculated by ray tracing are not matched by the simplified models, the general trend, however, is pretty well captured.

3.4.2 Assessment on Network Level

In the following we extend the previously conducted model comparison by projecting the existent path loss differences on a network level. The employed metrics are the packet reception probability, the packet inter-arrival time, the distance at which a first packet is being received, and the maximum distance starting from which regular successful packet receptions occur. The underlying motivation is to assess the impact of model differences on a level, which is comparable to a network simulation or even application perspective and hence to identify whether differences have to be expected for network oriented research. The evaluated propagation models are hereby the same as before, but this time with the additional consideration of fading aspects, as suggested by the respective simplified path loss models.

In order to bridge the gap from path loss to network perspective we employed Monte Carlo simulations to depict the stochastic packet reception process of a vehicle approaching an intersection. In total 1 000 000 runs per metric and radio propagation model were conducted under the following assumptions.

We implemented an analytical packet error rate model which has been proposed by Abrate et al. [AVS11], particularly to represent the characteristics of an IEEE 802.11p receiver and we configured it in accordance to previously stated assumptions of a QPSK

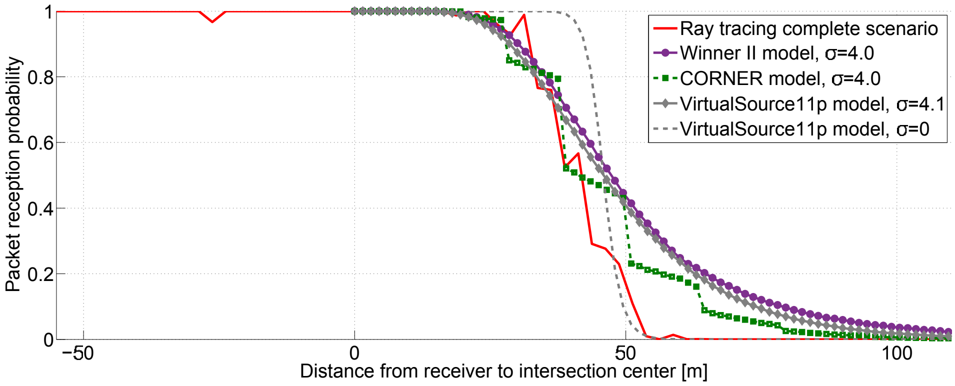


Figure 3.17: Average packet reception probabilities in the considered urban scenario, primarily in non line-of-sight conditions. For the Winner II, CORNER, and VirtualSource11p models, fading is modeled according to a normal distributed zero mean random variable. For ray tracing we average over a distance of 2.5 meters in driving direction, but also lateral to it.

modulation scheme and a data rate of 6 Mbps. Furthermore, the packet size was set to 400 bytes. Since the employed model determines the packet error rate depending on the signal to noise ratio (SNR), we calculated it, based on the assumption of a constant noise floor of $-99\ dBm$, a transmit power of $20\ dBm$ (EIRP), but we did not incorporate interference between multiple transmitters or variations in signal strength within the duration of one packet reception. In the considered scenario a vehicle is moving towards the center of the intersection with a constant velocity of $15\ m/s$ and in order to address small scale variations, which is of particular interest for the ray tracing modeling approach, we varied the starting point in steps of $0.25\ m$ in the directions of traffic, but also lateral to it. For the evaluation we primarily consider non line-of-sight conditions, i.e., situations where the receiver is located on the northwards road, since these are in general more critical w.r.t. to urban vehicular communication conditions. Further underlying assumptions are subsequently clarified during the presentation of the individual results.

Packet reception probability: We evaluated the packet reception probability, which is generally defined as the probability of a node r to successfully receive a packet p, being separated by a distance d to the transmitter t and visualize its outcome in Figure 3.17. The three considered path loss models were parametrized to best fit the scenario specifics and we additionally modeled small scale fading by means of a zero mean normal distributed random variable, as suggested by the respective simplified models. For ray tracing we considered the deterministically calculated path loss (already incorporating effects, e.g., due to multipath fading), but averaged over nearby neighbors in order to obtain the average packet reception probability and be reasonably able to visualize and compare its outcome.

While there are only minor differences observable between the Winner II and VirtualSource11p model, a choppier decline of the packet reception probability is observable when employing the CORNER model, which can be reasoned by the staircase shape increase of the path loss (cf. Figures 3.2 and 3.16). While at close proximity to the intersection center there are only minor differences observable, compared to the ray tracing modeling approach, these differences increase at larger distances, particular w.r.t. the distance at which there is a non neglectable probability of successfully receiving a packet. These differences can be reduced to the suggested fading modeling, according to a normal distributed random variable. Its exact impact becomes visible when comparing the packet reception probabilities of the VirtualSource11p model, with additional fading modeling ($\sigma = 4.1$) and without ($\sigma = 0.0$) in Figure 3.17.

Packet inter-arrival time (PIAT): The packet inter-arrival time is the intermediate time between two successful packet receptions at a receiver r, originating from the same transmitter t. For an inter-transmission time of 100 ms, a static transmitter, and a receiver moving with 15 m/s towards the intersection center, this basically corresponds to a reduced transmitter receiver separation of 1.5 $meters$ for every subsequent transmission attempt. Due to the monotonically increase of the path loss for the three simplified path loss models, there is a high probability of subsequent packet receptions being successful after an initial successful packet receptions (only being influenced by the characteristics of the packet error rate model) in case no small scale fading is considered. Consequently, the modeling of small scale fading has a crucial impact on an appropriate PIAT characteristic.

In order to evaluate the packet inter-arrival time we proceeded as follows: For ray tracing we varied the starting point in steps of 0.25 $meters$ as described earlier and determined the position where a first successful packet can be received. From this point on we evaluated following intermediate times between successful receptions as long as the vehicle was driving on the non line-of-sight street. A similar approach was followed for the other three models, by conducting a total of 1 000 000 Monte Carlo simulations per model to collect packet inter-arrival times for the respective path loss model including its suggested small scale fading parametrization. One simulation run hereby represents one approach towards the intersection center and measures the experienced packet inter-arrival times along the way. The resulting mean PIAT hence comprises of more than 20 000 000 measured values per model. The mean PIAT for ray tracing is in the order of 120 ms for an inter transmission time of 100 ms, while the calculated PIAT for the other three models varies in the range from 150 ms for the CORNER model up to 170 ms for the Winner II model. The observable differences can again be explained due to small scale fading modeling and consequent earlier first packet receptions for the simplified path loss models. For the sake of completeness we also evaluated the resulting PIAT without the consideration of small scale fading and obtained average PIATs in the order of 105 ms for all three considered models. The PIAT distribution of the VirtualSource11p model (with small scale fading modeled as a zero mean normal distributed random variable with $\sigma = 4.1$) is visualized in addition to the PIAT distribution according to ray tracing modeling in Figure 3.18.

It can be seen that in most cases immediate subsequent successful packet receptions are possible and that there is only a minor difference in the PIAT distribution if

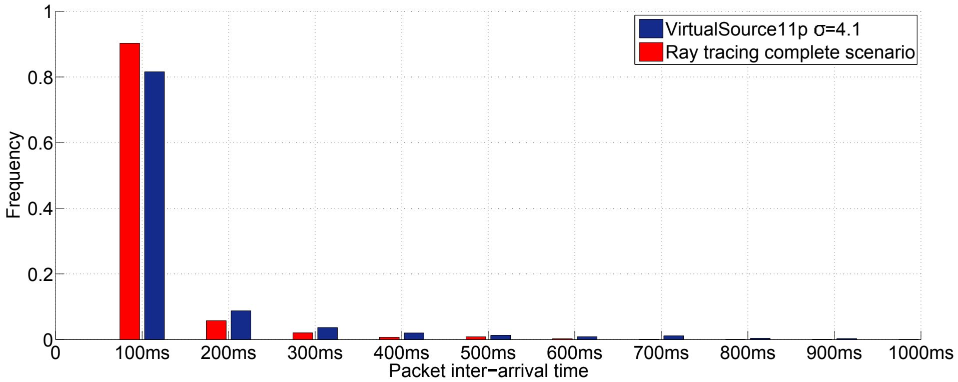


Figure 3.18: Histogram of the packet inter-arrival time in the considered urban scenario in non line-of-sight. The VirtualSource11p model is considered as representative for the simplified path loss models. Fading is hereby modeled according to a normal distributed zero mean random variable with $\sigma = 4.1$.

modeled by ray tracing or by means of an empirical model. However, it has to be kept in mind that while the ray tracing model is able to consider correlations between subsequent transmission attempts (for instance being influenced by a truck obscuring the intersection), modeling of fast fading according to a zero mean random variable assume them to be independent. Consequently, quite similar to previous insights, average characteristics are matched quite well by commonly employed urban radio propagation models, justifying their usage for network oriented research.

First packet reception distance: In order to evaluate the distance at which a first packet reception can take place we employed the same methodology as for assessing the PIAT. By fine grained variations of the starting point in driving direction as well as lateral to it we covered an extensive range of multipath propagation effects when employing the ray tracing model. For the CORNER, Winner II and VirtualSource11p models we again employed Monte Carlo simulation with previously mentioned assumptions.

In our considered scenario the earliest packet can be received within the range of 110 m $\pm 5m$ (combined distance: $d_{Tx} + d_{Rx}$ with $d_{Tx} = 60\,m$) on the non line-of-sight street towards the intersection center when employing ray tracing. Due to previously discussed fading effects, the average earliest reception takes place at a distance of $\approx 130\,m$ for the CORNER model, $\approx 140\,m$ for the VirtualSource11p model, and $\approx 150\,m$ for the Winner II model with a standard deviation of $\approx \pm 20\,m$ in each case. Without the consideration of additional fading, these distances decrease to $104\,m$, $106\,m$, and $107\,m$ with a std. deviation of 2.5, which then corresponds pretty well with the ray tracing result.

Regular packet reception distance: In addition to solely quantifying the distance at which a first packet reception is possible, we evaluated the distance from which point on regular packet receptions occur, i.e., from which distance on the remaining packet

Model	**Mean distance (±std. deviation)** **max PIAT: 500 ms**	 **max PIAT: 200 ms**
CORNER	112.0 $m(\pm 7.7)$	100.2 $m(\pm 6.1)$
Winner	117.7 $m(\pm 9.3)$	102.7 $m(\pm 7.0)$
VirtualSource11p	116.1 $m(\pm 9.0)$	101.2 $m(\pm 7.1)$
Ray tracing complete scenario	108.3 $m(\pm 6.5)$	100.0 $m(\pm 3.9)$

Table 3.3: Regular packet reception distances for the ray tracing, Winner II, CORNER, and VirtualSource11p models. Stated are the mean distances including the standard deviation from which point on subsequent receptions are possible with a PIAT of less than 500 ms/200 ms

inter-arrival times do not exceed a certain threshold. This threshold is exemplarily set to 200 ms and 500 ms in the following to assess whether differences have to be expected for an application requiring up-to-date information when employing a different modeling approach.

In Table 3.3 the mean combined distance under non line-of-sight conditions is stated for maximum accepted packet inter-arrival times of 200 ms and 500 ms. For a maximum accepted PIAT of 500 ms, there is a maximum deviation between ray tracing and the other modeling approaches of less than 10 meters. For a maximum accepted PIAT of 200 ms, i.e., at least every second packet has to be successfully received, all modeling approaches are quite in line, since i) the relative impact of fading decreases and ii) the packet reception probabilities at the according distances of less than 40 m to the intersection center are comparable (cf. Figure 3.17). The resulting differences should in most cases be reasonable accurate for assessing the application performance on a network level.

Summary: After the previous comparison of different urban radio propagation modeling approaches on solely a path loss level, the focus of this evaluation was to assess whether differences have to be expected on a network layer and for applications with different requirements. Similar to previous insights, the simplified models are obviously not able to match microscopic subtleties and could lead to wrong conclusions if not the average reception characteristic, but individual packet receptions are of interest as our evaluation has pointed out. The average behavior, however, is pretty well captured by all modeling approaches. Considering the quantitative evaluation by means of the packet reception probability, packet inter-arrival time, and regular packet reception we can hence conclude that the focus of the simplified urban radio propagation models to depict average situations for network oriented research is pretty well achieved.

3.5 Conclusions

In this chapter we have contrasted existing radio propagation modeling approaches for use in urban inter-vehicle communication scenarios with the purpose to evaluate whether the abstraction level of commonly employed urban radio propagation models is appropriate for network oriented research. In order to achieve this we employed ray tracing, a fine grained, but computational expensive modeling approach to perform a sensitivity analysis and identify the situations which are most determining for the dependability of urban inter-vehicle communication. While in line-of-sight conditions we identified three different propagation characteristics, namely i) a blank scenario with decisive multipath propagation effects, ii) a densely populated scenario with a multitude of obstacles compensating the effect of multipath propagation, and iii) obstructed line-of-sight conditions which severely influence radio conditions, there were barely differences observable in non line-of-sight radio conditions. We further revealed that the exact intersection shape only marginally influences its radio propagation characteristic.

Subsequently, we evaluated whether commonly employed radio modeling approaches are capable of appropriately representing the identified propagation characteristics on a path loss level and identified an adequate consistency between different modeling approaches, i.e., key characteristics in LOS and NLOS are appropriately represented in commonly employed light-weight propagation models. Our results hereby further indicate which model, respectively parametrization to use to best represent certain radio characteristics in urban environments and reveals the limits of simplified path loss models to depict occurring radio propagation outliers. A subsequent assessment which focused on pointing out deviations which have to be expected on a network and application layer perspective revealed that while for use cases where the single reception of a packet is decisive, commonly employed radio propagation modeling approaches might be not be appropriate, average packet reception characteristics are appropriately represented by all considered models.

From the perspective of network oriented research, i.e., having a focus on the interaction between multiple stations, the common objective is not to depict particular, but average situations. This can for instance be seen by commonly employed physical layer models, which abstract from signals and bits in favor of a faster and sufficiently still accurate packet level approach. Within the context of urban radio propagation modeling our analysis has hereby justified the abstraction level of currently employed models. Average conditions are appropriately represented and no significant deviations on a network level were present between light-weight path loss and fading modeling compared to fine grained ray tracing. Hence, in the spirit of multiscale modeling we can conclude that i) various abstraction levels for urban radio propagation models exist and are applicable, ii) key characteristics of urban radio propagation conditions are adopted, even in light-weight models and iii) commonly employed urban radio propagation models abstract on the right level for network oriented research.

Outlook

While within this chapter we have demonstrated the feasibility to employ ray tracing for network oriented research, which enables microscopic considerations and which we made use of to perform a sensitivity analysis, this approach is only reasonable if i) thorough scenario information is available and ii) the focus of the study is to consider severe outliers and not average conditions. The presented results of our sensitivity analysis can hereby serve as a starting point to identify situations which might be worth considering for future dependency assessment simulation studies as well as to quantify a minimum requirement of robustness which has to be ensured by inter-vehicle protocols and applications. Furthermore, for future simulation studies, the results indicate which simplified model or parametrization to use in order to represent which conditions.

One possible field of application for the presented ray tracing based approach is to find parametrization for commonly employed log-distance models to represent specific conditions with more precision, in case no field-operational tests are viable. As already previously discussed, the most promising fields for directly employing the ray tracing based approach are particular challenging situations, for instance to evaluate the impact a truck in intersection vicinity possesses on radio conditions and consequently for safety-critical applications. Particularly within this field of application, it is furthermore desirable to not just consider radio modeling with more detail, but combine it with a more fine-grained physical layer modeling as well. By means of this, not only timely variations, but also other characteristics, e.g., the frequency shift, of the received signals can be considered. Within the same context, the ray tracing based approach enables to consider the impact of interference due to multiple simultaneous transmissions on the received signals in more detail, compared to nowadays rather simplistic interference modeling approaches. The same methodology that we employed for evaluating the applicability of urban radio propagation models for network oriented research can obviously be applied for different scenario settings or traffic conditions, for instance highway scenarios. While for our analysis we solely focused on the path loss between transmitter and receiver, additional characteristics might then have to be considered due to higher relative velocities and longer propagation paths.

4

Decentralized Channel Coordination: MAC Protocols

In this chapter, we assess and contrast the capability of two fundamentally different decentralized coordination schemes to schedule periodic transmissions in a vehicular environment. These are on the one hand the random access based IEEE 802.11p CSMA, which is being envisioned for a first generation of inter-vehicle communication networks, and on the other hand, the reservation-based STDMA scheme, which is already being in use for the periodic exchange of messages between vessels. With respect to multiscale modeling this assessment indicates whether it is generally possible to abstract from a particular decentralized channel coordination scheme. From a dependability assessment point of view, the results point out which situations are particularly challenging for the respective MAC approaches.

In Section 4.1 the primary task of a medium access control protocol is described and its challenges within the vehicular networking domain are discussed. Following is an overview over related work, giving a brief summary over approaches which have historically been employed for coordinating the access in wireless networks as well as identifying to which degree CSMA and STDMA have been subject to scientific considerations in the past.

A comprehensive description of the STDMA protocol, including an analysis of its protocol features as well as identification of existing turning knobs is presented in Section 4.3. Subsequently, in Section 4.4 we present results from our conducted simulation-based assessment which primarily focuses on identifying strengths and weaknesses of STDMA to cope with particular situations and we highlight potential differences which have to be expected if STDMA instead of CSMA is being employed. Finally, Section 4.5 concludes this chapter by summarizing the insights w.r.t. to the raised research question and giving directions for future research.

Parts of this chapter have been previously published in [GMH^{+}13] and [GMHS14].

4.1 Challenges

One of the key challenges in vehicular networks is to coordinate the channel access among participating nodes in a way that interference between nodes sharing the same available bandwidth is minimized and reliable communication can be achieved as far as possible. Given nowadays wireless paradigms, the coordination of nodes hereby corresponds to finding a schedule which best satisfies a maximum separation distance between two simultaneously transmitting nodes or even withholds individual transmissions. In a centrally coordinated network, such as office devices being connected to an access point or in cellular systems, the coordination which device is allowed to transmit at which point in time and for which period can be done in a centralized fashion and be communicated to allocated devices or even be realized by polling. Within the domain of vehicular networks, a decentralized coordination scheme, where each node decides for itself when to transmit, is nowadays favored for the envisioned use cases. This is reasoned by a rapidly changing environment, but also by the necessity for transmissions at short notice under all circumstances, preventing a time consuming negotiation of a coordinator or allocating to it before being allowed to transmit a warning message. It should be noted that in the near future different use cases might arise where a centralized coordination scheme appears to be more beneficial and applicable, such as for platooning where strict time requirements have to adhered to, but communication relationships persist over a longer period of time.

In addition to severe radio conditions and a rapidly changing environment which have to be mastered by every coordination approach, a decentralized channel coordination scheme can be particularly challenged by hidden terminal issues due to only relying on a local view of its surrounding, as is pointed out in [Mit12]. The general issue with hidden terminals is that they can interfere with own transmissions, i.e., prevent the successful reception at a distinct node, but are themselves too far away to be coordinated with own transmissions. While within unicast networks solutions, such as RTS/CTS exist, these approaches are not applicable for a primarily broadcast oriented vehicular network.

There are a variety of fundamental medium access control mechanisms available, being based on space-, frequency-, time-, or code-division approaches. Space-division is implicitly employed by most approaches, since nodes being separated by a sufficient distance do not influence each other. By means of directional antennas this approach can further be employed in case the location of the recipient is known, but is generally not employable in networks where the position of interested nodes cannot be known beforehand. A code-division approach is rather sophisticated, since utilized codes have generally to be distributed and managed, which is challenging without any central coordination. A frequency-division is applicable in case multiple communication channels are required, but within the vehicular domain it is currently envisioned that every vehicle broadcasts its beacon messages on a single control channel, since the contained information might be of interest to every surrounding vehicle. Consequently, a variety of different time-division approaches have been proposed, with Section 4.2.1 giving a brief overview over approaches which have generally been employed in the past for coordinating the wireless channel on a time domain.

Within the vehicular community, there is the common consensus that the random access CSMA/CA scheme of IEEE 802.11p, as presented in Section 2.4.2, will be employed within the first generation of inter-vehicle communication system. It has been subject to rigorous analysis in the past, its "turning knobs" are understood (e.g., [Bia00], [Eic07]) and it has been shown to perform sufficiently well for the requirements of inter-vehicle communication networks (e.g., [Mit12]). Assessments which were carried out to quantify the impact of vehicular communication applications generally based their analysis on the assumption of the coordination ability of CSMA/CA and up to now it is unknown in which situations a different coordination scheme might yield an advantage or disadvantage, compared to CSMA/CA. Quite recently, the VANET community gained interest in a time-division reservation-based protocol, named Self-Organizing Time Division Multiple Access (STDMA). Within aviation and maritime domains, this approach is already standardized for the periodic exchange of status information between aircraft [Org04] and ships [ITU14], respectively.

While first results of STDMA within the vehicular domain look promising (e.g., [Sjö13], [AM12], [KP13]), there is yet a fundamental understanding missing in which situations and under which conditions STDMA is not able to successfully coordinate the channel access. Within this chapter we compare the abilities of STDMA and CSMA/CA to cope with characteristics which can occur in vehicular networks and evaluate its impact at various evaluation levels. On the one hand these insights allow to assess the dependability of the employed coordination scheme, by identifying particularly challenging situations (radio or traffic wise), which might require special precautions, for instance additional transmissions, for safety related concerns. On the other hand, reasoned by their fundamentally different coordination approaches, these insights justify whether it appears reasonable to abstract from a particular MAC realization for macroscopic modeling approaches, such as the one presented in Chapter 5.

Within this chapter we solely focus on a comparison of the ability of both protocols to schedule periodic messages, which serve as a backbone for most currently envisioned vehicular communication applications. In particular, we do not consider the ability of STDMA to handle high priority event messages and as such also do not strive towards giving a conclusive statement on which protocol might be better suited for future vehicular communication applications.

4.2 Related Work

Medium access control protocols have two main tasks. On the one hand they provide an addressing scheme on which individual nodes can be addressed on layer two and on the other hand they are responsible for coordinating the access on a (shared) medium. Since MAC addresses are generally already assigned by the hardware manufacturer, this poses no further challenge and we focus on related work w.r.t. coordination schemes for wireless environments and how they have been subject to scientific assessment in the past. Quite obviously, a static channel allocation is by no means conceivable within the vehicular domain and in combination with previously discussed FDMA, CDMA, and SDMA limitations, the focus in the following is on dynamic channel allocation approaches in the time domain.

4.2.1 Traditional Wireless Multiple Access Protocols

Research on wireless MAC protocols, coordinating the channel access on a shared medium, dates back until the 1970s. One of the first ones was the ALOHA protocol [Abr70], with the basic principle that a node is allowed to transmit whenever a packet has to be sent. In case a collision occurred, the node had to wait for a random amount of time and retransmit the complete packet. Quite obviously, this approach is most suited in case of only a minor channel load, with drastically increasing packet overlaps/collisions as the channel load increases. One improvement, which has been presented in the following years, extended the basic ALOHA protocol with slotted time frames [Rob75], noticeably increasing the throughput. The underlying idea was to divide the time in so called slots with a fixed length and nodes not being allowed to transmit at an arbitrary time, but having to align its transmission with the start of the upcoming slot. As a consequence, a transmission was only able to interfere with other transmissions occurring exactly in the same time slot (full overlap) and hence avoiding the possibility of partly overlaps with already ongoing or subsequently starting transmissions.

The Reservation-ALOHA protocol [CRW+73] maintained the slotted approach, but further incorporated a carrier sensing in which a node keeps track of which slots are being used by other nodes. Multiple slots are aggregated into one *frame* with a fixed length and a node sensing a slot as being occupied implicitly marks the same slot in the following frame as not available for own transmissions. In the same way reservations are "abandoned" by simply not making use of them. In case of upcoming transmissions a node randomly picks an unused slot and competes for it without any additional carrier sensing. In the following years, several extensions for the R-ALOHA protocol were proposed (e.g., [MR88], [ZHW91]), incorporating dedicated signaling periods where nodes communicate their view on slot assignments, addressing hidden nodes issues and informing neighbors about occurred packet collisions.

The general principle of Carrier Sense Multiple Access (CSMA) protocols is to sense the channel prior to an own transmission and decide on whether to send, depending on the current channel status as well as on specific characteristics of the CSMA protocol. In case the channel is sensed as idle, *1-persistent CSMA* immediately transmits, while *p-persistent CSMA* only starts transmitting immediately with a certain probability p and defers with probability $1 - p$. In case the transmission is postponed, the probability to transmit in the next free slot is again p and so on. *Nonpersistent CSMA* again transmits immediately if the channel is sensed as being idle, but waits a random period for a new carrier sensing in case the channel was occupied.

For a more general introduction and survey of wireless medium access control protocols we refer to Gummalla et al. [GL00] and to Chapter 7 of [HL09] for a more extended introduction to coordination approaches particularly in the vehicular domain. In the following we are focusing more specifically on IEEE 802.11 CSMA/CA and STDMA.

4.2.2 IEEE 802.11 Carrier Sense Multiple Access

The coordination scheme of IEEE 802.11p [IEE12] is based on a carrier sensing approach and has already been presented in detail within the fundamentals Section 2.4.2. In the following we will hence only focus on giving an overview in which way and to which degree CSMA in general, and IEEE 802.11p in particular has been subject to scientific evaluation before.

One of the firsts to evaluate the impact of hidden nodes in a CSMA coordinated wireless network were Kleinrock et al. [KT75] who analyzed the impact of different persistent variations on the achievable throughput and delay.

Bianchi [Bia00] performed one of the first analytical studies of an IEEE 802.11 DCF coordinated network and analyzed the impact of varying initial contention window sizes on the achievable throughput. His work was picked up in following years and several refinements were proposed which addressed simplifications that were made within the original work. For instance, Hou et al. [HTL03] extended the model to incorporate a consideration of hidden nodes for the DCF coordination scheme with RTS/CTS access mechanism, Duffy et al. [DML05] eliminated the original requirement of a saturated network, i.e., every station always having packets to send, and Pham [Pha05] introduced a more realistic radio conditions consideration by employing a probabilistic Rayleigh channel model. Li et al. [LZ06] further considered the impact of the *capture effect*, the ability of advanced receivers to switch to a newly incoming strong signal at the expense of dropping a currently synced on, but weaker signal. Analytical considerations of the EDCA-based quality of service extension (being included in the IEEE 802.11p standard in this way) have, for instance, been performed by Zhu et al. [ZC03], Engelstad et al. [EØ05], and Han et al. [HDT+12].

While analytical considerations have an apparent advantage for understanding relationships and determining optimal parameters, their expressiveness is often limited due to the challenge or practical impossibility of a comprehensive consideration of every existing aspect, such as radio or mobility aspects and receiver capabilities. Consequently, simulation-based assessments are a frequently employed approach, particularly within the vehicular domain.

Crow et al. [CWKS97] employed simulations to assess the coordination ability of the PCF and DCF schemes of the IEEE 802.11 draft standard in 1997 with a consideration of a bursty error channel, but without incorporating the effect of hidden nodes. Weinmiller et al. [WWEW96] focused on analyzing the key aspects of the DCF coordination ability and identified the backoff strategy as well as RTS/CTS mechanism to have a determining impact on the overall network performance.

Within the vehicular domain Eichler [Eic07] investigated the impact of an EDCA-based QOS extension and it is concluded that this approach generally works fine, the assignment of messages to QOS categories, however, requires particular care since too many high priority messages strongly degrade its suitability. Stibor et al. [SZR07] analyzed the suitability of the IEEE 802.11p draft for coordinating the wireless channel, but did not employ commonly used packet reception probability metrics, but focused on potential communication neighbors and communication duration. Bilstrup et al. [BUS08] evaluated the delay characteristic of an IEEE 802.11p coordinated vehicular network and concluded that the impossibility to state an upper bound access time might be problematic for time critical, typically safety-related use cases. Torrent-Moreno et al. [TMJH04], [TMCH06], [TMCSEH06] performed simulation-based assessments in a rather saturated network and quantified the impact of different radio propagation modeling, i.e., different channel characteristics, by means of evaluation metrics, such as the packet reception rate, the channel access time, but also by means of a novel metric, the packet level incoordination, which directly measures the ability to coordinate the channel access at first hand. Schmidt-Eisenlohr [SE10] greatly extended the parameter space (message size, generation rate, transmission power) to quantify the impact of interference on the performance of IEEE 802.11p, but also to characterize due to which reasons packets might be dropped. Mittag [Mit12] characterized the situations in which CSMA is not able to successfully coordinate the channel in more detail, by employing bit level, instead of previously employed packet level simulation and concluded that IEEE 802.11p is able to coordinate the channel sufficiently well.

To conclude, several decades of intensive research of CSMA/CA in general and IEEE 802.11 in particular have lead to an understanding of its coordination ability. The influence of its “turning knobs” has been studied analytically and by means of simulation-based assessment over a long period of time in office, but more recently also in the context of vehicular environments. Consequently, situations have been identified where the coordination scheme of CSMA is severely challenged.

4.2.3 Self-Organizing Time Division Multiple Access

Self-Organizing Time Division Multiple Access (STDMA) is a TDMA-based approach, which does not require a centralized coordinator, but instead employs a coordination scheme which is based on each node piggybacking information on its own future transmissions to its neighbors. It was presumably invented by Håkan Lans who received a corresponding patent in 1996 [Lan96], which was, however, reexamined in 2010 with the result that all claims were canceled. As already previously mentioned, the STDMA approach has been standardized and is widely deployed within the Automatic Identification System (AIS) [ITU14] for an exchange of heartbeat messages between maritime vessels and it is the basis of the VDL Mode 4 [Org04] of the International Civil Aviation Organization for a similar use case in aviation.

The division of the time domain into slots with a fixed length and time synchronization between participating nodes enable a TDMA-based approach, contrary to CSMA, to plan ahead, i.e., to find a best schedule which node is allowed to transmit in which slot by exploiting available lookahead. In case there are more transmissions than available slots, multiple nodes can/have to transmit within the same time slot, which is called slot reuse. Generally it is attempted to avoid slot reuse by nodes which are close together (due to occurring interference), but it is unavoidable and not detrimental to schedule concurrent transmissions by nodes which do not influence each other. Within the literature this challenge is addressed by Spatial TDMA approaches which try to find a best scheduling among all participating nodes. Björklund et al. [BVY03] considered the spatial reuse issue within a TDMA organized ad-hoc network and proofed that even under simplistic assumptions, e.g., a static network which is centrally coordinated, it is NP-hard to find an optimal schedule. For this reason, it is rather common within related work to employ heuristics, for instance Funabaki et al. [FT93] proposed an artificial neural network model to figure out a close to optimal schedule. Grönkvist et al. [GNY04] quantified the throughput gain of an *optimal* TDMA scheduling approach compared to a traditional TDMA approach and found it having the highest impact under low connectivity between nodes and large network sizes.

One of the first to analyze characteristics of a self-organizing TDMA coordinated network was Kjellberg [Kje98] who derived basic analytical models to quantify the achievable capacity and throughput of such a network. Similar to the analytical considerations of CSMA, this approach gives a great first overview of the scope, however, it does not allow to incorporate each and every influencing aspect. With a focus on maritime environment Wu et al. ([WCZG07], [WSY$^+$07]) performed a simulation-based assessment to identify the influence of channel load, mobility, and bit error rate (BER) on the achievable throughput. Their results, however, only show resulting general trends, no comparison to other coordination schemes is performed and no conclusions and insights are drawn from the achieved results.

In 2005 Ebner [Ebn05] evaluated the use of a self-organized TDMA scheme in a vehicular environment and compared its reception rate and achievable throughput compared to IEEE 802.11, ALOHA, and slotted S-ALOHA under varying channel load situations. Overall, STDMA achieved slightly better results than CSMA and a proposed extension to STDMA, exchanging slot allocations with neighbors to cope with hidden node issues, even increased the advantage of STDMA in the considered scenario. Bilstrup et al. similarly proposed the STDMA approach for a deployment in vehicular environments in 2007 and primarily focused on evaluating the channel access time of STDMA compared to CSMA ([BUSB08], [BUSB09b], [BUSB09a], [SBUS10], [SUS11]). It is concluded that while the maximum channel access time of CSMA is not upper bounded, which might be problematic for time sensitive safety-related use-case, the slot reuse approach of STDMA ensures real-time demands by offering an upper bound limit at which a node is allowed to transmit at the latest. By evaluating the slot reuse percentage and minimum distance between two nodes utilizing the same slot, the authors further gave a first impression of the coordination ability that STDMA can achieve on average, however, without going in-depth and analyzing in which situations successful coordination cannot be achieved. Previous insights are summarized in [Sjö13], where CSMA and STDMA are, amongst others, compared by means of the packet reception rate or access delay metric with an overall slight benefit of STDMA over CSMA. Quite similarly, in late 2012, Khairnar et al. [KP13] evaluated CSMA and STDMA by means of a simulation-based assessment on an Indian highway scenario. However, several simplistic assumptions are made therein, for instance a circular deterministic channel model is employed, which assumes that transmissions can be sensed up to a fixed distance. In addition to delay evaluations, slot reuse statistics are presented which indicate at which distances slots are being reused. However, the impact of slot reuse is not discussed or related to other achieved results and no direct comparison to CSMA/CA is drawn.

In [ASU+11] Alonso et al. discuss potential traffic situations which might be challenging for an STDMA coordination scheme. These are i) the start-up phase where plenty of new nodes who are unaware of any slot reservations enter the network, ii) cluster merging where two organized and stable vehicle clusters merge together and have to reorganize themselves, and iii) emergency situations where in addition to beacon messages, event notification have to be scheduled and transmitted. These issues, however, are only discussed and no evaluation is being performed. In [AM12] Alonso et al. consequently investigated the stabilization time, i.e., the time it takes a MAC protocol to reach a reliable operation state and found this time to be lower for STDMA compared to CSMA, particularly under high channel load. Additionally, the throughput of an STDMA coordinated network was analyzed by Alonso et al. [ASM11] by employing radio propagation conditions which were collected during a measurement campaign. The considered network, however, only consisted of a maximum of five vehicles and might thus not be too representative.

In 2012 the European Telecommunications Standards Institute (ETSI) published a technical report [ETS12] in which the packet reception rate and access delay of CSMA and STDMA are compared. With respect to the packet reception rate it is concluded that STDMA benefits from its synchronized approach and achieves slightly better performance under all conditions with a more distinct difference as the transmit power and channel load increases.

While previous results slightly favored STDMA for most considerations, other insights exist as well. Moser et al. [MWS12], for instance, point out that CSMA achieves lower average channel access times than STDMA, but of course without any guaranteed upper bound. The authors furthermore evaluated the packet reception rate and concluded that particular for rather high channel loads a significant differences has to be expected, with CSMA achieving a higher packet reception rate at close distances and STDMA further away. Within their analysis, Stanica et al. [SCB10] argue that CSMA can achieve higher packet reception rates due to the suppression of upcoming transmission requests under rather high channel loads (which could, however, have negative effects for time-critical safety related use cases), contrary to STDMA where slot reusing results in every packet being transmitted, even in case the channel is already oversaturated. In Table 4.1 we briefly summarize the characteristics of STDMA as identified within previously presented related work.

To summarize, while there are various evaluations available, which primarily focus on assessing the packet reception rate and channel access delay in a particular situation, it is yet not clear or even contradictory i) which situations benefits which coordination scheme to which degree, and ii) which protocol mechanisms or parametrization of STDMA influences the performance to which degree (which has been extensively studied for CSMA). Contrary to already available work, our focus is not to compare both coordination schemes in yet another scenario, but to fundamentally understand which conditions can result in STDMA not being able to successfully coordinate the channel and quantify the likelihood of these to occur. To emphasize this approach again, we first identify decisive protocol mechanisms of STDMA, evaluate the effect of different protocol parametrization, and based on these insights assess and compare the

Related work	Identified characteristics of STDMA (in comparison to CSMA)
[Sjö13], [ETS12]	⊕ Deterministic upper bound channel access delay ⊕ Higher probability of packet reception (PPR) ⊕ Higher detection distance(only [Sjö13]) ⊖ Higher average channel access delay
[AM12]	⊕ Shorter stabilization time
[MWS12]	⊕ Higher PPR at large distances under high load ⊖ Worse PPR at close ranges under high load
[SCB10]	⊕ Better channel access time in an oversaturated network ⊖ Worse PPR at close distances in an oversaturated network

Table 4.1: Comparison of the strengths and weaknesses of STDMA as identified within related work

ability of STDMA and CSMA to cope with a variety of challenges a MAC protocol is required to deal with in a vehicular environment. The achieved results not only expand the understanding of how well STDMA is able to cope with previously not considered situations, but also gives a more general insight of the strength and weaknesses of an STDMA coordinated vehicular network.

This fundamental approach to study characteristics of the underlying STDMA coordination mechanisms was just recently supported by the authors of [GH15] who contributed a first analytical model for a metric which we introduced in [GMHS14] to describe how many simultaneous transmissions are occurring per slot. Despite several simplistic assumptions, e.g., no mobility or fading, the model allows to assess the impact of a few protocol parametrization.

4.3 STDMA Protocol Overview

The objective of this section is to present a complete and detailed description of the STDMA protocol, followed by an in-depth, fundamental analysis and evaluation of the protocol elements that govern its function. We analyze the protocol theoretically, by first assuming idealistic conditions and identifying potential causes that can lead to reception failures, including a discussion of the impact of protocol parametrization. We are thus able to identify the limitations and weaknesses of STDMA that emerge only from the protocol itself, i.e., we can answer the fundamental questions of how slot allocation collisions can occur in STDMA. Subsequently, we remove the assumption of idealistic conditions and briefly discuss how real world factors could induce additional slot allocation collisions. Within Section 4.4 the insights of this section are then picked up and quantitatively evaluated by means of simulation-based assessment.

It is emphasized again that we solely focus on the ability of STDMA to schedule periodic heartbeat messages with a fixed length in the following. In particular, this implies that we do not consider how exceptional event messages could be scheduled, preferably at short notice and in coexistence with other ongoing transmissions.

4.3.1 Detailed Protocol Description

As most other TDMA-based approaches, STDMA divides the time in so called frames that last for a certain duration, and those frames into equally sized transmission slots that accommodate a single packet transmission. The explanation given in this section is basically based on the version of the ITU-R protocol specification in 2010 [ITU10] with minor adjustments and additions to adapt the protocol for a usage in inter-vehicle communication networks.

The structure of this subsection is as follows. First, basic assumptions and the fundamental protocol elements are explained in order to convey a basic understanding of the protocol. We then specify the random access strategy for transmitting the first packet, the slot reservation mechanism, and the slot re-reservation mechanism.

Assumptions

Within this section the following assumptions are made for clarity, but without loss of generalization

1. all stations generate packets at a fixed (report) rate $r \geq 1$ packets/frame,
2. all packets adhere to a fixed maximum size s (which translates to a fixed transmission duration),
3. internal clocks of all stations are synchronized, not in absolute terms (i.e. so that all stations share the same time) but such that all nodes know exactly when a new time slot starts and when it will end; note that synchronization of frame boundaries is not required. In practice, time synchronization with an accuracy of significantly less than 1 μs (cf. [EWR04], [ERHL02]) which should be sufficiently accurate (compared to the assumed guard interval of 6 μs per slot) can be easily achieved by making use of the Global Positioning System which is anyhow a prerequisite for vehicular networks. In case no GPS signal is available the ITU-R standard [ITU10] proposes a decentralized approach, which synchronizes to the neighboring station which itself has the most neighbors.

Outline of fundamental principles

The lifetime of a station in STDMA is divided into four different phases: *initialization*, *network entry*, *first frame*, and *continuous operation*. These ensure that each station first obtains an understanding of the slot allocation status, then announces its presence to the network, and afterwards performs the initial slot allocation for all transmissions to be made during one frame. Afterwards, the continuous operation phase is entered in which only slot re-allocations are carried out.

Using these terms, Figure 4.1 explains the fundamental principles that are applied in the network entry and the first frame phase. After having listened to the channel for one complete frame, the next i slots are considered for random access. The number of slots is subject to configuration (e.g. [ITU10] sets i to 150 slots). The station then randomly selects an available slot out of these i slots in order to

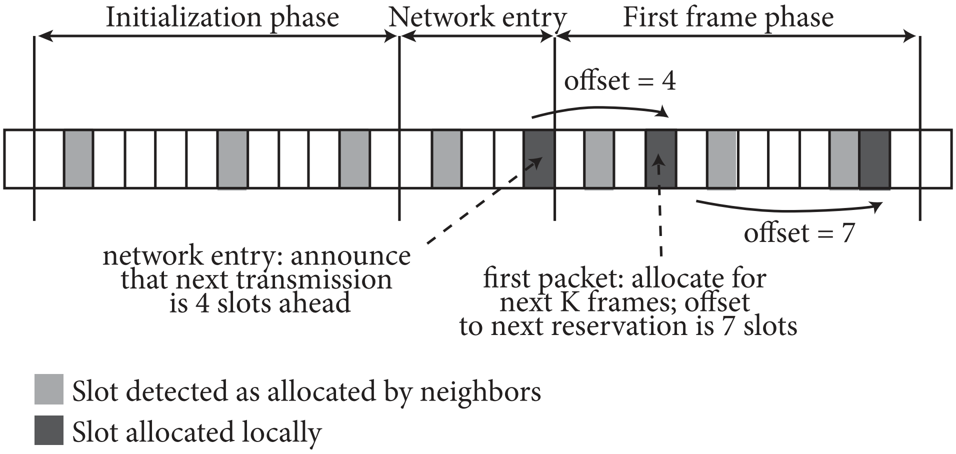


Figure 4.1: Principles of STDMA: after startup, a station listens to the channel for a complete frame to determine the slot allocation status (*initialization phase*). In the following *network entry phase* the station performs a random access to announce its presence and its first slot reservation. The slot afterwards marks the beginning of the *first frame phase* during which further slot reservations and their duration are announced. Once every slot reservation within the *first frame* is transmitted, the *continuous operation phase* begins. Figure first published in [GMH+13].

1. introduce its presence to the network,
2. and pre-announce the next slot it is going to use

Hence, before transmitting the network entry packet, the station already has to decide which slot it will use for its first reservation. As a result, neighboring stations that receive the network entry packet become aware of the presence of the station and the transmission slot it is going to use next.

When using this first pre-announced transmission slot (termed first packet in Figure 4.1), the station repeats the same process: it announces the next slot it is going to use, and in addition indicates how often it will re-use the current slot. In STDMA, the terms *timeout* and *offset* are used to refer to the duration of a reservation in frames and the difference in slots between two transmission slots. Each STDMA packet must contain a timeout value, an offset value, and the geographical position of the sender.

Initialization phase

During the initialization phase, a station is only listening to the channel and monitoring the status of each single slot. Each slot can be in one of the following states (in order of decreasing priority):

1. *Internally Allocated*: a slot is considered to be internally allocated if the station has allocated this slot to itself. The state is maintained as long as the internal timeout value is greater than zero.

2. *Externally Allocated*: a slot is considered to be externally allocated if a transmission has been observed in the past that indicated that this slot is going to be used. Note that it is not required that this past transmission has been observed in the same slot. It is also possible that this external allocation has been communicated through the offset parameter in a different slot. The state *externally allocated* is maintained as long as the recorded timeout value is greater than zero.

3. *Busy*: a slot is considered to be busy if either (a) a packet has been detected in the same slot of the previous frame but the packet failed to be decoded successfully, or if (b) the average energy level at the receiver during the same slot of the previous frame was above the configured clear channel assessment (CCA) threshold[1]. The busy state is kept until the end of the next frame[2].

4. *Free*: a slot is considered to be free if all of the following conditions hold: (a) no observed transmission in the past has indicated that this slot is going to be used in the future; (b) no preamble was detected in this slot; (c) the average energy level at the receiver measured during the same slot of the previous frame was below the configured CCA threshold[3].

After the station has listened to the channel for one frame, it should have a good understanding of the slot allocation status in the network (since every participating station transmitted at least one packet within the duration of one frame) and be able to derive sound allocation decisions for the next frame(s). The monitoring activity is never stopped to keep the station updated over time. When updating the local slot allocation status table, each station uses the following policies: (1) the state observed in the previous frame is only overwritten if the new state is of higher priority (*Internally Allocated* > *Externally Allocated* > *Busy* > *Free*); (2) when a slot is already marked as externally allocated upon reception of a packet, the maximum of the old and new timeout values is used; (3) a state transition from externally allocated to free is only applied if the reservation duration has expired, or if the slot has been detected to be free at least 3 consecutive times.

Network entry phase

The network entry phase is the time period starting directly after the initialization phase and ending when the packet that introduces the station's own presence has been broadcast. This packet is referred to as the *network entry packet* in the following. The selection of the time slot for this network entry packet is based on the random access time-division multiple access (RATDMA) protocol of [ITU10] and is specified as follows:

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[1] The state *busy* is not explicitly modeled in [ITU10] but has been added for clarification.

[2] As future work, it could be considered whether further optimization, e.g., by incorporating the information gained by the *offset* parameter, could help to avoid blocking this additional frame.

[3] The conditions (a) and (b) are not explicitly stated in [ITU10] and have been added for clarification.

1. Define a selection interval (SI) of potential transmission slots and let it cover the next i transmission slots (e.g. $i = 150$)
2. Establish a set of potential transmission slots by including all slots marked as *free* in this SI[4].
3. At the beginning of each potential transmission slot, randomly decide whether to use this slot or not.

Essentially, the RATDMA protocol employs a p-persistence mechanism to decide in which of the potential transmission slots the network entry will be performed. The probability $p(k)$ for a transmission in a potential transmission slot k is defined as

$$\begin{aligned} p(0) &= \tfrac{1}{n(0)} \\ p(k) &= p(k-1) + \tfrac{1-p(k-1)}{n(k)}, k > 0 \end{aligned} \tag{4.1}$$

where $n(k)$ denotes the number of slots remaining in the potential transmission set, beginning from slot k to the last slot. Importantly, the number of free slots, denoted by $n(k)$, is updated (i.e. reduced) in case one of the potential transmission slots is detected as externally allocated. The exact definition is given in §3.3.4.2 of [ITU10].

Since confusion exists in the literature it is worth re-iterating that the network entry packet is a one-time transmission in order to announce the first packet of the first frame, i.e., the network entry packet signals the offset to the next slot being used. A description of how this next slot is selected follows.

Basically, the same random access approach could be employed for transmitting packets which have not been pre-announced, but these are obviously more prone to slot collisions, compared to transmissions with prior notification. The ITU-R standard [ITU10] consequently proposes to avoid random access transmissions except if not possible otherwise, e.g., for the *network entry*.

First frame phase

Once the station has announced its presence, the station enters the *first frame phase*, which is depicted in Figure 4.2. The objective of this phase is to announce and reserve additional slots in order to fulfill the configured report rate. Assuming that one frame comprises N slots and the station is configured to transmit r packets per frame, the allocation is performed step-by-step as follows:

1. Set the nominal increment (NI) value to $\lfloor N/r \rfloor$.
2. Randomly select a nominal start slot (NSS) out of the first NI slots.

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[4] In this matter we diverge from [ITU10], by not considering *externally allocated* slots for the network entry as long as at least one *free* slot within the *SI* is available.

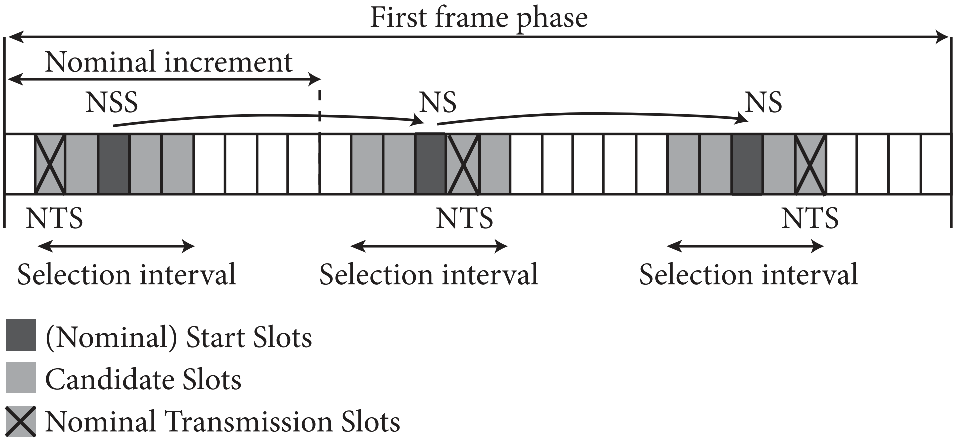

Figure 4.2: First frame phase: one of the first nominal increment (NI) slots is randomly selected as nominal start slot (NSS). Figure first published in [GMH+13].

3. Derive additional $r - 1$ nominal slots (NS) by subsequently adding NI slots to NSS.
4. For the NSS and each NS:
    (a) Construct a selection interval (SI) by adding $\lfloor (N/2r)s \rfloor$ number of slots to the left and to the right, with s being the SI ratio, e.g. 20 %.
    (b) Compile a set of candidate slots within this SI (normally all *free* slots, details are explained in the near future)
    (c) Randomly choose one of these candidate slots as nominal transmission slot (NTS)

When announcing the allocation of a selected slot, a random timeout value is drawn from statically defined minimum and maximum timeout limits. Hence, each allocated slot gets its own timeout value.

Continuous operation phase

After the first allocation within the first frame phase is performed, the station enters continuous operation. During this phase a station performs re-allocations whenever the internal timeout of a slot expires. The rules for re-allocation are the same as in the first frame phase, however, a station is allowed to stick to the current slot if no candidate slot is available. Furthermore, when re-reserving a slot, the semantics of the offset value changes. While it normally indicates the offset to the subsequent transmission, it then indicates the offset to the newly selected slot in the next frame.

Candidate slot set compilation

The compilation of candidate sets is, as seen earlier, needed throughout slot reservation and re-reservation. According to §3.3.1.2 of [ITU10] it has to adhere to the following set of rules:

- There should always be at minimum C candidate slots to choose from unless the number of candidate slots is otherwise restricted due to lack of position information (e.g. when there are too many *busy* slots in the selection interval).
- The candidate slots are primarily selected from *free* slots.
- If less than C slots are free, *externally allocated* slots are included in the candidate set.
- Externally allocated slots are added in order of decreasing distances to the current station.
- Externally allocated slots may only be added if the (local) station is not already intentionally reusing another slot of the same (remote) station.
- All candidate slots have the same probability of being chosen, regardless of their state.
- If there are still less than C candidate slots available the station selects one slot out of the reduced candidate set.
- If no candidate slots can be found, the station should not reserve a slot in the SI. This is unlikely to happen since this would only be the case if all slots are un-decodable.

With the rule set above, each station can select the slots to be used. The rule set aims to ensure that simultaneous transmissions are either avoided or spatially separated as much as possible. In the latter case, it is further the objective to reuse at most one slot of the same remote station.

Parametrization

In general, the following protocol parameters can hence be tuned: minimum number of candidate slots, frame duration, minimum and maximum reservation timeout, selection interval size, maximum number of slots to consider for random access during network entry, and guard interval between two slots. Table 4.2 shows the values considered as default by [ITU10]. The only changes made are a reduction of the frame duration to one second and the guard interval has been adjusted to protect against realistic worst-case path delays in 5.9 GHz radio channels.

4.3.2 Discussion of Slot Allocation Collisions

The focus of the following analysis is to identify situations in which packet (or slot allocation) collisions can occur in STDMA, i.e., to identify the events leading to a situation in which two stations transmit at the same point in time and to further analyze how these collisions then affect the coordination ability of the protocol.

Parameter	Value
Min. number of candidate slots	4 slots
Frame duration	1 sec
Min. reservation timeout	3 frames
Max. reservation timeout	7 frames
Selection interval ratio	0.2
Max. duration of network entry	150 slots
Guard interval (per slot)	6 μs

Table 4.2: Default STDMA protocol configuration, based on [ITU10], but adjusted for the 5.9 GHz inter-vehicle communication radio channel

Perfect conditions

To address these questions, we first assume that all stations are within each other's communication range, that all packets that are received in the absence of interference can be decoded successfully, and that the number of slots per frame is greater than the number of slots required to satisfy each stations demand. Under these assumptions, which are later relaxed, only the following three situations can lead to packet collisions:

1. Two (or more) stations startup at approximately the same time and randomly select the identical slot for **network entry**.

2. All random access slots of a station's **network entry** phase are marked as busy or externally allocated. In this case, the entering station will reuse the slot allocated by the station furthest away.

3. The candidate slot set has been enriched to satisfy the minimum number of candidate slots requirement and an externally allocated slot was selected while performing a **(re-)reservation**.

The first situation can be dismissed as an unlucky occurrence and there can be no counter measure against it in traditional wireless networks, which are incapable of 'listen-while-talk'. The second situation can easily occur if the maximum duration of the network entry phase is too short to find a gap of available slots within this period.

The third situation can, on the one hand, occur if there are still free slots available within the SI, but too few to satisfy the configured number of required slots in the candidate set. In this case, even though free slots are available an externally allocated slot might be selected. This situation can easily be avoided by reducing the number of required candidate slots to one. On the other hand, if no free slots exist in the SI, the candidate set contains only externally allocated slots, forcing the station to (knowingly) re-use a slot. An immediate question is therefore: how easily can STDMA run into this last situation? Clearly, this situation is triggered when the channel is overloaded, but can also otherwise occur whenever the nominal (start) slots of all neighboring nodes are not uniformly distributed and the selection interval size is not large enough to avoid local congestion. As soon as the nominal (start) slots accumulate in certain areas of a frame the channel becomes overloaded in these areas and remains unused in the areas not covered by the selection intervals. One solution to mitigate this effect is to increase the selection interval size, which however has the drawback that packet inter-transmission times become less predictable.

It should be noted that the above reasons for packet collisions are of statistical nature. Hence, it is possible that these events do not occur at all over a given time period as their probability of occurrence is very low. Further, additional influences which are later discussed, such as station mobility can also lead to slot allocation collisions. Yet, independent of the reason, the consequence is always the same: transmitted control information (slot offsets and reservation durations) are prone to be non-decodable by remote stations, due to drastically reduced SINR resulting from packet collisions in these slots. Eventually, this might prohibit these remote stations from obtaining a proper understanding of the slot allocation status or re-reservation decisions.

Hence, an additional important question to answer is how existing slot allocation collisions in particular, or the lack of control information in general, affect subsequent coordination decisions of STDMA. Specifically, it is worth investigating whether slot allocation collisions are contagious as the lack of control information might support the introduction of new allocation collisions in subsequent re-reservation processes, or whether the protocol is able to resolve the situation. To answer this question, we refer to the microscopic example in Figure 4.3a which illustrates the slot allocations of four stations using a transmission rate of 2 Hz. As can be seen stations 1 and 2 are not involved in any allocation collision, however, stations 3 and 4 use the same slot for their first transmission[5]. Consequently, station 1 and 2 will not be able to successfully decode the information in this slot, hence, they do not know for how long this slot will be used. Even more importantly, they will miss the notification to which slot station 3 and 4 switch once they perform a re-reservation. What can happen then is illustrated in Figure 4.3b: assuming that both, station 3 and 4, as well as station 2 perform a re-reservation in the same frame, the probability arises that station 2 selects the same slot as station 3 and/or station 4. As station 2 performs a re-reservation after these two stations (while not being able to decode their re-reservation notification), it is not aware of the newly selected slot(s) and may choose (with a certain probability) the same slot. Hence, if there is already a slot allocation collision existing, the probability exists that either the same one or more than one new collisions are present after the re-reservation process. One of these outcomes is exemplarily illustrated in Figure 4.3c.

Non-perfect conditions

Quite obviously, previously made assumptions do not hold in a realistic vehicular environment where hidden nodes are inevitable, severe fading conditions might exist and mobility is a key property. As a consequence, additional causes can exist which can lead to slot allocation collisions, with an overview of commonly influencing factors given in the following.

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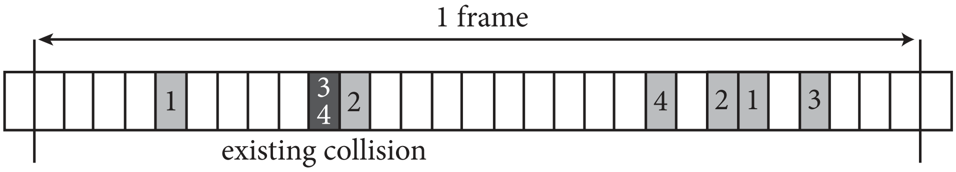
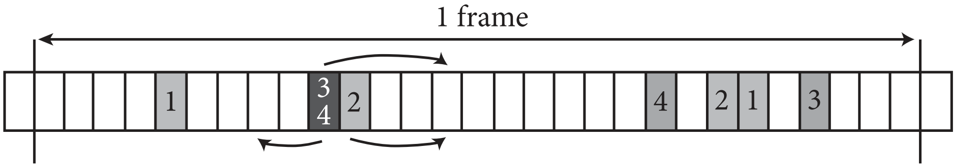
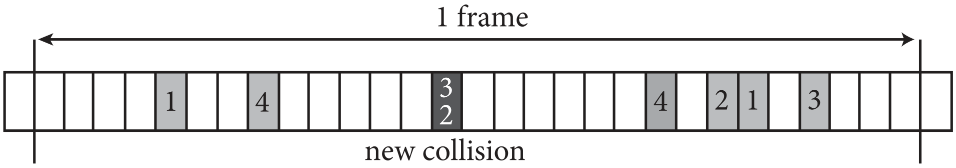
[5] Without loss of generality and for the sake of simplicity we assume in this example that all stations use the same frame boundary.



(a) Before re-reservation process



(b) Reservation decisions of stations 2, 3 and 4



(c) After re-reservation process

Figure 4.3: Illustration of what can happen during re-reservation of two stations that are already involved in a slot allocation collision: (a) allocation status before re-reservation; (b) decisions made by stations during re-reservation; (c) allocation status after re-reservation. Figure first published in [GMH+13].

- **Hidden Nodes:** Given the coordination approach of STDMA to not forward any reservation information, but only making it available within a one-hop range, two nodes are hidden from each other as soon as no more direct communication between these two nodes can take place. From the perspective of these two nodes, concurrent transmissions (slot reusing) might be alright, since their mutual influence, e.g., by means of interference, is sufficiently small. However, for a third node who is, for instance, able to communicate with both other nodes, these simultaneous transmissions could result in both transmissions, including contained reservation information, being non decodable. Such a situation is visualized in Figure 4.4 with node (2) not being able to decode the re-reservation information of node (1) and randomly selecting the same transmission slot. The general issue and impact is hereby the same as within the situation visualized in Figure 4.3.

- **Mobility:** The issue with mobility in an STDMA coordinated network is the general shortcoming of reservation-based protocols to quickly adjust to a rapidly and steadily changing environment/neighborhood. For instance, imaging a scenario where two perfectly coordinated vehicle clusters are moving towards

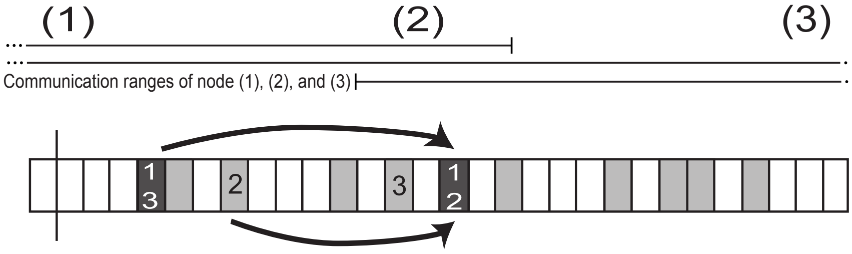
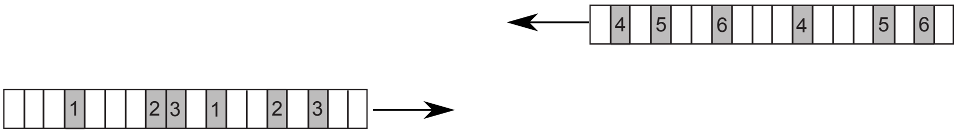
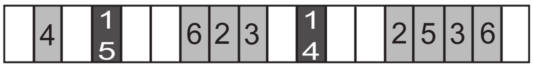


Figure 4.4: Illustration of how a hidden node (Node (3)) can lead to incoordination between two nodes that are within each other's communication range (Node (1) and (2)) with STDMA.



(a) Before merging



(b) After merging

Figure 4.5: Illustration of what can happen in case two perfectly coordinated vehicle clusters merge together: (a) slot allocation status before; (b) slot allocation status after merging. No re-reservation is assumed to be ongoing in the meantime.

each other in a highway scenario (cf. Figure 4.5a). As long as both clusters are sufficiently separated, it is perfectly fine if the same slot is allocated by a node in each cluster. Then, as the vehicles are approaching each other, first, previously discussed hidden node issue will emerge as soon as the interference range of both clusters overlap. Then, some time later, vehicles which previously allocated the identical slot come into communication range (cf. Figure 4.5b), but are unable to immediately resolve this slot allocation collision.

– **Channel fading:** Contrary to idealistic conditions, vehicular communication networks generally experience severe fading conditions (cf. Chapter 3), resulting in temporary variations on which stations are able to successfully decode incoming transmissions. Due to these variations a station might miss vital reservation information which could very well have a detrimental effect on the coordination ability of STDMA.

To summarize, this section pointed out that there are a variety of situations which can result in STDMA not being able to successfully coordinate the channel and slot allocation collisions to occur. The reasons and causes therefore are of fundamentally different nature compared to CSMA, e.g. missed reservation information for STDMA vs. bad luck with CSMA, and consequently different strengths and weaknesses in coordination capability can be expected.

Even under perfect conditions, situations are feasible in which a slot is *unnecessarily* occupied twice. However, it is intuitively clear, that under perfect conditions, the more deterministic STDMA might be better suited than CSMA which heavily relies on random access. Its exact characteristic, the influence of previously discussed protocol parametrization and whether existing slot allocation errors can be resolved is not that easy to guess, however. Similarly, it is commonly assumed that severe fading and mobility has a more detrimental effect on the coordination ability of STDMA than for CSMA, but its exact impact has not been considered so far. While on an abstract level it hence appears intuitive that STDMA, which plans ahead, has more difficulties to handle unforeseen circumstances compared to CSMA, and vice versa, that CSMA, which performs no planning, might eventually not be able to utilize the channel with the same efficiency than STDMA, its exact characteristic depend on particular conditions and is not that easy to answer.

In the following we consequently perform an extensive empirical study to address these issues and current shortcomings. In particular, we identify i) to which degree the coordination capability of STDMA is influenced by its parametrization and ii) how severe the coordination capability is influenced under different radio conditions and in particular situations.

4.4 STDMA (Empirical) Protocol Analysis

In this section results from our conducted simulation-based evaluation are presented and discussed. First, we present the general methodology and employed metrics, before step-by-step the impact of individual aspects are analyzed. We therefore employ a systematic multi-aspect evaluation approach which is described in the following and visualized in Figure 4.6.

In the previous section we already identified the situations, i.e., internal protocol processes, but also external influencing factors which can result in incoordination in an STDMA network. In this section we first quantify how often these situations occur, but also evaluate how the coordination ability is hereby influenced. We start by assessing the influence of STDMA's protocol parametrization on its coordination capability and opt for a parametrization which is suited for an inter-vehicle communication deployment. Based on this parametrization we subsequently assess the severity of communication aspects on the performance of STDMA and CSMA and identify situations where one or the other protocol has its strengths and weaknesses. In a final step we then add mobility aspects and by making use of previous insights are able to derive to which degree mobility changes the overall picture. The combined assessment, not only of the coordination ability of both protocols, but also by assessing its impact on a network level by means of the packet delivery ratio and packet inter-arrival time, helps us to address the overarching objective of this chapter to identify whether and under which situations differences between STDMA and CSMA have to be expected.

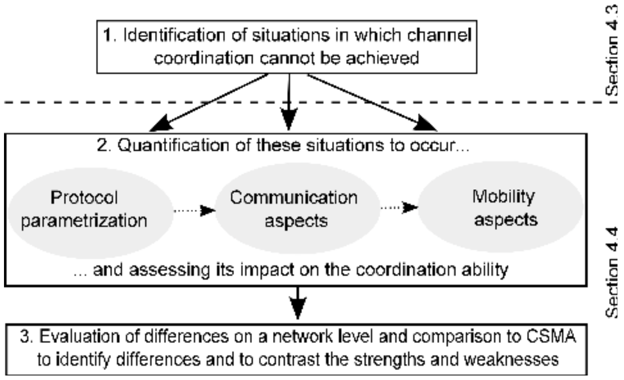


Figure 4.6: Utilized systematic evaluation approach to identify differences and to contrast the strengths and weaknesses of STDMA in comparison to CSMA

4.4.1 Methodology

In the following a brief overview over the general evaluation approach and considered scenario variations is given, before the metrics are presented. For all our simulations we employed the well-known NS-3 [RH10] network simulator in version 3.16 and since no open or publicly available implementation of STDMA existed, we extended it with an own implementation which we made publicly available[6] for reproducibility, but also to encourage further research. For CSMA we employed default DCF settings and hence did not consider the impact of different EDCA access categories. Exemplary studies with EDCA's *best effort* configuration only yielded a marginally deterioration in coordination ability of less than 1 % for a channel load of approx. 50% (due to a longer AIFS), with increasing differences as the channel load increases.

In general, there are a multitude of configurations which can be varied and which all in one way or the other influence the achievable performance of MAC protocols. For instance, these are i) protocol parametrization, such as the reservation duration, the selection interval size, or the minimum candidate set size, ii) communication conditions, such as radio propagation conditions, the severity of fading, but also the transmission rate and power, iii) scenario settings, such as the vehicle density, their startup behavior, the packet size or mobility characteristics, and iv) receiver capabilities, such as for instance the carrier sensing sensitivity, required SINR for a successful packet reception, or the support of packet capturing. Due to its combinatorial complexity it should be quite apparent that an extensive and concurrent investigation of all these influencing factors is not reasonable and we hence employed multiple evaluation studies with each focusing on an individual aspect. The hereby resulting scenarios are discussed in the following.

Scenario layout and general settings

In all considered scenarios we generated packets with a fixed size of 400 bytes at a fixed generation rate which is, however, subject to a small jitter. We assumed a physical layer data rate of 6 Mbps, following the suggestion of Jiang et al. [JCD08]. In total three different scenario were considered, namely the *protocol parametrization*, *communication aspect*, and *mobility* scenarios which are being discussed in the following:

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[6] The implementation can be found at `http://dsn.tm.kit.edu/ns3-stdma.php`

1. **Protocol parametrization scenarios**

   In order to evaluate the influence of different protocol parametrizations we positioned a varying number of stations (42, 63, and 84) on a straight road without considering any mobility. In combination with the 400 byte data packets, a considered transmission rate of 10 and 20 Hz, and a physical layer data rate of 6 Mbps, this amount of vehicles generate exactly 25 %, 50 %, 75 %, and 99 % channel congestion[7].

   The medium access control implementation is set once to CSMA and once to STDMA in each setup. When running an experiment with STDMA, we further vary the minimum number of candidate slots, the reservation duration and the selection interval ratio according to the values given in Table 4.3 which further summarizes the selected configuration. To study the influence of protocol startup, we simulate each scenario twice: once with all stations starting up one after the other (using a little bit more than one frame as separation which constitutes the best case for STDMA, since two nodes cannot select the identical slot for their network entry), and once with stations starting up randomly using a rate of 4 nodes/s.

   Overall we depicted two fundamental communication situations that any distributed medium access control has to address: i) perfect, and ii) imperfect decoding capabilities without considering their cause or particular communication characteristic. In any case the wireless channel is configured such that each station can sense each other's packet transmission. Additionally, in the first connectivity situation all stations can successfully decode each other's transmissions as long as there is no interference (i.e., an interfering transmission will prohibit the successful reception of reference and interfering transmission). In the second connectivity situation, successful decoding of transmissions is only possible if the distance between sender and receiver is less or equal than approx. 60 % of the carrier sensing range. This artificial limitation of the range over which packets can successfully be delivered, ensures an effective limitation of the degree up to which a common view on the reservation status can be established among stations. Note that for this consideration we abstracted from the precise cause of this limitation (which will be picked up in later scenarios), since we were only interested in its general impact.

2. **Communication Aspects Scenarios**

   Subsequent to assessing the influence of different protocol parametrizations and load situations on the ability of STDMA to coordinate the channel we fixed these parameters according to previous results in order to solely focus on communication aspects hereinafter.

   Similar to previous scenario we positioned stationary nodes on a straight road with a length of 2 100 meters. We assumed equally distributed inter-vehicle distances with a vehicle density of 85 vehicles/km, resulting in a total of 177 vehicles.

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[7] To clarify: when using a 6 Mbps data rate, 50 % channel congestion refers to 3 Mbps of transmissions that can be carrier sensed.

Scenario and application layer			
Number of stations	42, 63, and 84 stations		
Packet size	400 bytes		
Transmission rate	10 Hz, 20 Hz		
Transmission power	20 dBm		
Startup behavior	1 node/sec deterministic, 4 nodes/sec randomized		
STDMA-based MAC		**CSMA-based MAC**	
Frame duration	1 sec	Slot time	13 μs
Initialization phase	1 frame + 1 selection interval	Contention-window size	15 slots
Min. candidate slots	1 slot, 4 slots		
Reservation duration	3 frames, 7 frames, $\mathcal{U}[3,7]$ frames, endless	AIFSN	2
Selection interval ratio	20 %, 40 %, 60 %, 80 %, 100 %		
Guard interval per slot	6 μs		

Table 4.3: Application and medium access control layer parameters used for the STDMA protocol parametrization scenario.

Every node is configured to transmit 10 packets per second with a packet size of 400 bytes and in combination with a data rate of 6 Mbps this results in an experienced channel load of 10 % per 100 m carrier sensing range (CS-range). A CS-range of 500 meters consequently leads to experienced 50 % channel congestion. We successively start up our nodes with a rate of one node per second with previously described randomized startup behavior, i.e., a random offset between the start up times is included. While every node is actively participating in the vehicular network (transmitting and receiving) we are only evaluating packets that are transmitted from vehicles positioned in the central 100 meters of the road. This way boundary effects are avoided that result in a significant drop of the experienced channel load at the edge of the scenario. A summary of important settings can be found in Table 4.4.

In total three different radio models were considered in order to point out different characteristics of the MAC protocols to handle specific situations and to work out its impact on the performance of these protocols.

(a) **Fixed range communication model:** This model serves as a basis for the further evaluation, since it facilitates interpretation of the achieved results and thus allows to better highlight the causes leading to incoordination or packet drops. The received signal strength at a receiver located d meters away from the transmitter is set to the transmission power if $d \leq communication\ range$, otherwise the received power is zero. This ensures that a packet is successfully delivered if i) the distance between transmitter and receiver is less than the configured communication range (CR) and ii) no other node within the CR of the potential receiver is interfering or, in other words, transmitting a packet with a timely overlap.

Scenario, application layer and common MAC settings	
Number of stations	177 (85 vehicles/km)
Transmission rate & power	10 Hz, 20 dBm
CS/RX-threshold	-91/-88 dBm
Radio Model	Fixed range, Power law, Nakagami fading
STDMA-based MAC	
Min. candidate slots	1 slot
Reservation duration	$\mathcal{U}[3{,}7]$ frames
Selection interval ratio	20 %

Table 4.4: Application and medium access control layer parameters used for evaluating the impact of communication aspects on the coordination ability. Parametrization of the CSMA MAC is in accordance to the information given in Table 4.3.

(b) **Power law communication model:** This model employs a log distance communication model with a path loss exponent of 1.85 and a reference loss of 59.7 dBm at a distance of 1 m. These parameters arise from measurements performed by Kunisch et al. [KP08] in a highway environment. Contrary to the fixed range communication model this model allows to separate between a carrier sensing range and a receiving range, the range at which a signal is strong enough that a potential receiver can sync to the signal. If not otherwise stated we assumed a CS-threshold of -91 dBm and an RX-threshold of -88 dBm, which equals a CS-range of approx. 600 meters, when only considering deterministic path loss, and a receiving range of approx. 400 meters. It should be emphasized that the reception threshold poses an artificial limitation up to which signal strength a receiver tries to sync to a signal which does not necessarily exist with the same rigorous characteristic in reality. With regard to quantifying the impact of communication aspects on the coordination ability of STDMA, this limitation, however, allows to clarify existing interdependencies. For our following analysis, we then removed this additional limitation. The decrease of signal strength over distance leads to two general differences, compared to a fixed range communication assumption: i) packets might still be successfully received even if a packet reception is being interfered, if the resulting signal to interference and noise ratio (SINR) for the current reception is still sufficient, ii) non successful packet receptions might occur even if the potential receiver is within the deterministic communication range, since packets might be dropped by the packet error rate model(which is the NistErrorRateModel of NS-3 in our case), whose probability depends on the SINR. As a consequence, the results achieved by using this model considers the distance at which an incoordination occurs in more detail, where interferences in close range are generally worse than if the interferer is located far away.

  (c) **Nakagami fading communication model:** This model employs fading by a Nakagami distribution [Nak60] on top of the power law path loss model explained previously. The Nakagami m-parameter hereby indicates the severity of fading, where a low value indicates severe fading (e.g. $m = 1$ equals Rayleigh fading) and a higher value (e.g. $m = 3$) represents a reduced fading intensity. Generally speaking, fading leads to temporary signal gains or decreases and hence to variations which stations are successfully able to decode an incoming transmission. This model thus allows us to assess the effect of temporary radio propagation variations on the overall performance that the protocols are able to achieve.[8]

3. **Mobility Scenarios**

   In order to assess the impact of mobility we employed two different scenarios with the focus to highlight on the one hand the microscopic difference on how STDMA compared to CSMA is influenced by mobility, and on the other hand to assess the overall average impact on the coordination ability and subsequent performance metrics. Radio propagation conditions are modeled according to the Power Law path loss model with fading according to Nakagami $m = 2$.

   Contrary to previous *communication aspect* scenarios, we did not further artificially limit up to which signal strength a station is able to synchronize to an incoming signal. Instead, we considered every incoming signal with a signal strength of at least $-95\,dBm$, which can be justified by a reasonable chance to detect the *preamble* as well as be able to decode the *signal header* from this point one with the configured noise floor of $-99\,dBm$. Whether the *data symbols* (payload) and as a consequence the entire packet can be successfully decoded is then, in a subsequent step, solely decided by the NistErrorRateModel [PH10] of NS-3. It should be noted that due to different encoding schemes of the *signal header*, compared to the *data symbols*, this can result in being able to successfully decode the header, but not the payload. The carrier sense threshold is still configured to be $-91\,dBm$. Without the consideration of fading and interference, this parametrization resulted in no successful packet receptions at distances larger than 800 meters.

   (a) **Highway scenario:** This scenario consists of a straight road with a length of 2 100 m and a total of 126 vehicles which are divided into two groups. The first group is positioned in the center and is not moving all the time. The second group is moving from one side of the road to the other with a constant speed of 20 m/s and is hence passing the *stationary group* at some point in time. The *moving group* only starts moving after a sufficiently

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[8] Typically, a Nakagami distribution is used to model small-scale fading, i.e., variations that occur several times while a packet is transmitted, whereas slow-fading is assumed to be log-normal distributed and not varying in the time of a single packet transmission. For our analysis the specific characteristic of fading is not crucial and we decided to model it as independent and identically distributed large-scale fading by means of a Nakagami distribution.

long initialization period so that both group's coordination should be settled. Prior to the spatial approach there is no communication possible between stations which are not within the same group.

(b) **Circular scenario:** In this scenario vehicles are moving with a constant speed of 20 m/s on two circular discs with a radius of approx. 1 000 m in the opposite direction. The inter-vehicle distance between vehicles is chosen to be 40 meters which results in a total of 629 vehicles which are present. The Power Law path loss model in combination with a transmit power of 20 dBm and a carrier sense threshold of −91 dBm results in approx. 120 vehicles which can be carrier sensed and with a transmission rate of 10 Hz this results in approx. 71 % channel load. Under the considered communication settings a vehicle is only able to communicate with a small sub set of vehicles and as a consequence there are constantly new encounters between vehicles, which have to resolve existing slot allocation collisions when employing STDMA.

Employed metrics

Before the protocol performance is evaluated, we wait until all stations are started up, and then monitor each station for 180 seconds to track its perception and to collect all the data needed to quantify the performance metrics described below. To achieve statistically significant results, each setup is simulated multiple times with a different seed for the random number generator. It should be noted that there are only marginal differences between the resulting runs, which is due to an extensive averaging over a multitude of sending or receiving events of all participating stations. As a consequence, the confidence intervals for most evaluations are too small to be visible. In order to evaluate the performance, the following primary performance metrics are used.

Definition 4.1 (Packet Level Incoordination, PLI [Mit12]) *The packet level incoordination, as observed from the perspective of a node r and one of its generated packets p, describes the probability that, at least, one node s, s ≠ r, transmitted a packet q during the transmission period of p.*

The PLI is a transmitter-based metric which captures how well a MAC protocol is able to prevent simultaneous transmissions which most protocols try to avoid in a first step. It solely captures the probability of simultaneous transmissions, but does not incorporate their severity. Since generally simultaneous transmissions at close range are more severe than transmissions further away, its significance has to be regarded with respect to the distance at which the incoordination occurred.

Definition 4.2 (Slot Occupation Distribution, SOD) *The slot occupation distribution describes the probability that a transmission slot is used by exactly i nodes, $i = 0, 1, 2, 3....$ When n_i represents the number of slots occupied by exactly i transmissions and $n = \sum_{i=0}^{\infty} n_i$ is the total number of slots, these probabilities can be calculated as $\frac{n_i}{n}$.*

For a specific distance, the SOD characterizes how many nodes are reusing the same slot. Ideally, a slot is either used not at all or there is just one transmission occurring among nodes which are within each other's interference range.

Definition 4.3 (Packet Delivery Ratio, PDR) *The packet delivery ratio, as observed from the perspective of a node r, describes the probability that a packet transmitted by node r is successfully delivered to a potential receiver s and is calculated as:*

$$PDR = \frac{\sum packets\ successfully\ delivered\ to\ node\ s}{\sum packets\ sent\ at\ node\ r},\ with\ s \neq r.$$

Since in general we are not interested in a specific transmitter/receiver combination we aggregate and average over multiple combinations with a similar spatial separation distance d. The PDR is a receiver-based metric and implicitly considering factors like i) the interference caused by incoordinated transmissions or ii) the capability of the receiver to, for instance, cope with noisy receptions (needed SINR) or being able to switch to a stronger signal at the expense of a weaker signal that is dropped (packet capturing).

Definition 4.4 (Packet Inter-Arrival Times, PIAT) *The packet inter-arrival time distribution, as observed from the perspective of a node r, describes the temporal distribution between two successful receptions from node s, s ≠ r.*

The PIAT incorporates a temporal aspect in the receiver-based evaluation and allows to assess whether packet drops occur equally distributed or follow each other, since e.g. two nodes are using the same slot over and over again when using STDMA.

Since previously presented metrics are not independent of each other we discuss existing relationships in the following. More specific, we present the relationship between PLI and PDR, which can be connected by making use of the SOD. We are therefore assuming an STDMA-based approach, since the concept of time slots simplifies our analysis, the general relationship between PLI and PDR, however, stays the same for CSMA.

For a first analysis we assume a highly idealistic small scale scenario with a fixed range communication model and every node within the communication range of each other. Under these assumptions a transmission is successfully received if and only if one slot is exactly occupied by one station, whereas no packets can be decoded if a slot is used by more than one station. Under these conditions the PLI and PDR can both be derived from the SOD as follows:

$$PLI = \sum_{i=2}^{\infty} \left(\frac{(i-1)n_i}{a} \right) \tag{4.2}$$

$$PDR = \frac{n_1}{a} \tag{4.3}$$

where a equals the number of overall transmission attempts, calculated as $a = \sum_{i=1}^{\infty} (in_i)$. For calculating the PLI we have to sum up the number of nodes experiencing incoordination in a certain time slot (which is every node except the first one transmitting in this time slot) and divide it by the overall number of transmission attempts. For calculating the PDR only the slots have to be summed up with exactly one transmission taking place and divided by the overall transmission attempts. Looking at Equation (4.2) and Equation (4.3) the relation can be stated as:

$$PDR = 1 - c * \mathrm{PLI} \tag{4.4}$$

where the parameter c depends on the slot occupation distribution. Note: For another definition of the PLI, as $PLI = \frac{a-n_1}{a}$, the relation can be simplified as $PDR = 1 - PLI$.

In a more realistic scenario with hidden terminals and varying characteristics of the radio channel the PLI can still be calculated by using the slot occupation statistics, however, calculating the PDR in the same way is no longer possible. The reason therefore is that slot reusing might become a successful option or, in other words, packets transmitted by multiple nodes within the same time slot do not necessarily prohibit successful receptions of these packets at distinct nodes. In order to determine whether a packet is successfully received, plenty of factors have to be considered, like on the one hand the receiver characteristic that determines the packet error rate or the ability to perform packet capturing. On the other hand the radio characteristic also plays an important role in determining the interference caused by simultaneous transmissions at a receiver. All these aspects are hard to evaluate in an analytical way and are thus contrasted and quantitatively measured in the following by means of a simulation-based study.

4.4.2 Results for Protocol Parametrization

In this subsection the results of our conducted simulation-based assessment are illustrated, which focused on the one hand to quantify the frequency as well as severity of the situations identified in Section 4.3.2 and on the other hand to investigate how sensitive the coordination ability of STDMA is, w.r.t. a proper protocol parametrization.

First, results under perfect conditions are presented, i.e., a vehicle can always successfully decode every packet in the absence of simultaneous transmissions, while our second study only assumes that vehicles are able to sense each other's transmissions, but are not necessarily able to decode them.

Results for perfect decoding capabilities

Low to medium channel congestion: We start with summarizing the results for the setup with 42 stations using a fixed packet generation rate of 10 Hz. Together they generate a load of 25 %, which is low enough to generate no packet-level incoordination at all, no matter how the STDMA protocol is configured. This performance is expected, as the network entry collision reasons listed in Section 4.3.2 are either very unrealistic (identical slot for network entry) or have been avoided as the initialization phase has been extended in order to cope with the underlying issue. (Re-)reservation collisions just do not happen as the selection interval spans 34 slots in the worst case (SI of 20 %) and it is unlikely that the nominal start slots generate a local congestion that is dense enough to block all of them. Needless to say that 24.8 % of the slots are used exactly by one station, and 75.2 % not at all.

		3 frame reservation		endless reservation	
SI	Min CS ($\mathcal{C}$)	Min value	Max value	Min value	Max value
20 %	1 slot	1.6 %	6.8 %	4.4 %	6.6 %
	4 slots	8.3 %	11.5 %	9.1 %	10.9 %
40 %	1 slot	1.6 %	2.8 %	1.9 %	3.2 %
	4 slots	13.1 %	13.8 %	4.6 %	5.5 %
60 %	1 slot	1.5 %	3.1 %	1.2 %	1.6 %
	4 slots	12.1 %	12.7 %	2.8 %	2.9 %
80 %	1 slot	5.8 %	7.8 %	0.8 %	1.0 %
	4 slots	12.9 %	13.1 %	2.0 %	2.4 %
100 %	1 slot	10.2 %	11.7 %	0.6 %	0.9 %
	4 slots	14.1 %	14.3 %	1.5 %	1.8 %

Table 4.5: Minimum and maximum PLI values that were observed in the *84 station and 20 Hz scenario*, when using either a 3 frame or endless frame reservation duration.

The situation changes if the 42 stations generate 20 packets/sec, increasing the offered load to 50 %, as the configuration of STDMA does slightly matter now. Although the level of incoordination is still very low (ranging from 0.02 % to 0.18 %), all configurations in which a selection interval size of 20 % (which equals 17 slots) in conjunction with a minimum candidate set size of 4 is used exhibit incoordination. As investigations reveal, the (re-)reservation collision reason strikes in these setups, i.e., there would be slots available, but as the candidate set had to be enriched with externally allocated ones, there is a chance that an already externally allocated slot is selected. Apparently, these slot collisions could have been avoided. It also turns out that the problem is not related to the congestion level at all. If 84 stations generate 10 packets/sec, which equals to an offered load of 50 % as well, the probability of incoordination reason number 3 drops to zero again as the selection interval size is increased to 34 slots due to the reduced packet generation rate.

High channel congestion: Incoordination becomes almost inevitable if a setup with 84 stations and a packet generation rate of 20 Hz is used. This combination yields a congestion level of approx. 99 % (1 680 required slots versus 1 694 available slots in total per frame). Table 4.5 lists the recorded PLI values over a wide range of protocol configurations: different selection interval sizes, one or four required candidate slots, and two different slot reservation durations. The influence of the network entry duration has been abstracted in this table due to space limitations, but is indicated through the minimum and maximum observed PLI value in each combination of the above settings.

The first immediate observation is the negative impact of the requirement of at least 4 candidate slots. As already pointed out before, this leads to incoordination that could have been avoided.

Second, the effect of an increased SI-size for a 3 frame reservation is contrary to endless reservation - increasing PLI with increased SI size for 3 frame reservation and decreasing PLI with increased SI size for endless reservation. This can be explained by the fact that with endless reservation there is only one initial slot reservation per

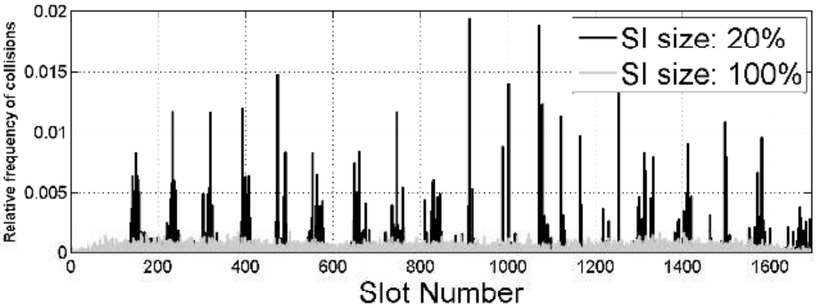


Figure 4.7: Slots in which collisions occurred in the STDMA coordinated 99 % load scenario with a 3 slot reservation duration and an SI of 20 % and 100 %, respectively. Figure first published in [GMH+13].

nominal slot taking place. As discussed in the last section, this reservation can only be successful if there is, at least, one free slot available within the selection interval. Consequently, the probability of a successful initial slot reservation increases with a larger SI size. Importantly, even with an SI-size of 100 % the resulting selection interval (with a transmission rate of 20Hz) results in only 84 slots. Thus, with a total of 14 free slots within a frame of 1 694 slots and possibly non equally distributed nominal slots, this can still lead to collisions due to lack of free slots within the SI. With a reservation duration of only 3 frames the PLI tendency is the opposite. In contrast to endless reservation, there is not just one initial reservation, but in addition one re-reservation taking place per NS every three seconds. As discussed in the protocol analysis, slot allocation collisions can be rather contagious and lead to a lot of new collisions, comprising previously collision-free nodes. In our scenario, with a high load of 99 % and frequent synchronized re-reservations every 3 seconds exactly this effect is observable. The SI size acts as a collision domain, resulting in more localized collisions with a smaller SI size and spread over the entire frame with an SI size of 100 %. In Figure 4.7 this effect is visualized by plotting the slots in which a collision occurred during one simulation run for an SI size of 20 % and 100 %, respectively.

Third, the difference between the minimum and maximum PLI values, representing the effect of different network entry durations, is overall rather small and less decisive, compared to the other considered parameters.

Comparison to CSMA: For the next evaluation, considering random reservation durations, we limited the parameters of STDMA to an SI size of either 20 % or 40 % and a minimum CS of just 1 slot. These values are in accordance with the results shown in Table 4.5 and influenced by the fact that lower SI sizes contribute to more predictable inter-transmission times. Table 4.6 states the resulting PLI for this parametrization of STDMA and for CSMA with the settings stated in Table 4.3. The PLI values of CSMA are increasing from about 1 % with 50 % load, to 3.6 % with 75 % load to 10.6 % with 99 % load (without any packet transmissions being suppressed). STDMA on the other hand is perfectly able to coordinate the channel with a load of 50 %. With a load of 75 % and an SI size of 20 %, it occasionally happens that no free slot within the SI is available. With 99 % load and perfect decoding capabilities the PLI for STDMA still

	CSMA	STDMA	
#nodes/rate		SI 20 %	SI 40 %
42/20Hz (≈ 50% load)	1.07 %	0 %	0 %
84/10Hz (≈ 50% load)	1.14 %	0 %	0 %
63/20Hz (≈ 75% load)	3.61 %	0.01 %	0 %
84/20Hz (≈ 99% load)	10.65 %	2.68 %	0.96 %

Table 4.6: PLI under varying load with perfect decoding capabilities.

	CSMA	STDMA	
#nodes/rate		SI 20 %	SI 40 %
42/20Hz (≈ 50% load)	1.40 %	6.16 %	6.36 %
84/10Hz (≈ 50% load)	1.51 %	6.2 %	6.48 %
63/20Hz (≈ 75% load)	4.01 %	10.99 %	11.27 %
84/20Hz (≈ 99% load)	10.42 %	18.81 %	18.39 %

Table 4.7: PLI under varying load with non perfect decoding capabilities.

stays rather low with better overall results for an SI size of 40 %. Further investigations with scenarios consisting of 168 vehicles transmitting with 10Hz and 336 vehicles transmitting with 5 Hz (resulting in the same network load of 99 %) depict a slightly better PLI of ≈ 1% with an SI of 20 %. This effect can be explained by an increased SI interval size due to the reduced transmission rate.

Influence of starting-up behavior: When starting up several nodes per second, we observe occasional collisions due to two stations randomly selecting the identical slot for network entry. The probability hereby increases with the network load, as less free slots are available for stations to choose from for their network entry. However, the resulting PLI for every simulation carried out did not differ noticeably and we can hence conclude that simultaneous start up behavior which has to be expected realistically does not pose any further burden for STDMA.

Results for non-perfect decoding capabilities

In order to get a basic understanding of how STDMA is influenced by non-decodable but still detectable packets we changed the communication model for the following evaluation. For CSMA this does not introduce any new burden, since it is still able to sense the channel as busy over the entire simulation scenario strip with a length of 500m. However, STDMA can only decode and consequently extract reservation information from nodes positioned within a range of 300m. All other nodes still contribute to load on the channel and occupy slots that are sensed as *busy*. The resulting PLI values over the same parameter space considered before can be found in Table 4.7.

As expected, PLI values for CSMA are not significantly different to the ones observed with perfect decoding. For STDMA the situation changes drastically as even with a load of just 50 % the PLI increases to ≈ 6 %. The reason for this is twofold: First, reservation announcements of nodes further away than 300 meters cannot be 'understood' and, second, re-reservations are not understood either, which can

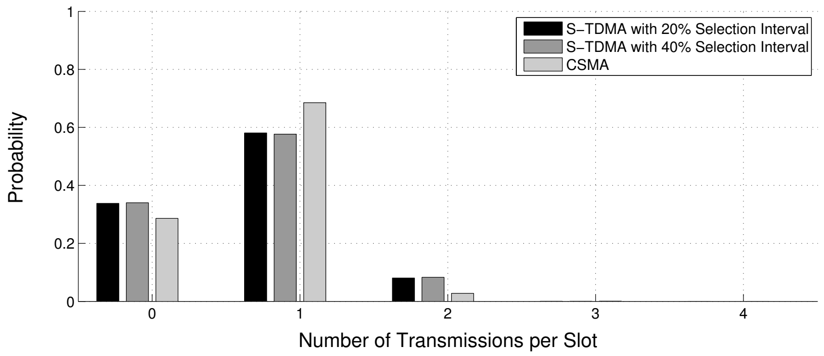


Figure 4.8: Slot occupation distribution for the 63 nodes 20Hz scenario (≈ 75 % load) with non-perfect decoding capabilities.

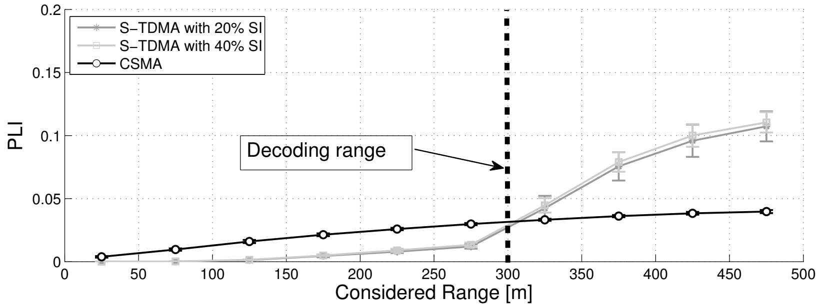


Figure 4.9: Packet level incoordination w.r.t considered range of a node for the 63 nodes 20Hz scenario (≈ 75 % load) with non-perfect decoding capabilities. Figure first published in [GMH⁺13].

have the effect that a slot is still considered as busy for one additional frame, even though the node switched to another slot and the previous slot is now free. Collisions resulting from non-perfect view on the vicinity are, thus, inevitable. With increasing load the PLI increases up to ≈ 18.5 % , whereby no clear difference between an SI size of 20 % or 40 % is observable. This effect is depicted in Figure 4.8 by means of a slot occupation distribution for the 63 nodes 20Hz scenario. Even though, there are still several free slots available (transmissions per slot = 0) some slots are used twice.

Besides the PLI value itself, we also investigated the locations and the distance of the nodes that interfered with each other, respectively. Figure 4.9 visualizes the PLI for varying ranges, i.e., we evaluate the PLI if only incoordination of nodes within a certain distance are considered. It is clearly visible that up to a distance of 300 meters, which corresponds to the decoding range in our scenario, STDMA is still able to coordinate the nodes better than CSMA. The incoordination then likewise significantly increases, as the nodes are no longer able to extract reservation information.

Summary

As our results show, STDMA is able to avoid slot allocation collisions as long as all transmitted packets are successfully received by neighboring stations – even if the cumulative load offered by all stations is high. While under perfect communication conditions and a high channel load the impact of parametrization is clearly visible and primary dependent on an appropriate selection of the SI-Interval and minimum candidate set size, its impact is neglectable under low to medium channel load and diminishes under non perfect communication conditions.

As our evaluation pointed out, the introduction of non decodable, but only sensible nodes drastically influences the coordination ability of STDMA since vital control information might be unavailable. Under these conditions, the coordination ability of STDMA obviously drops below the one of CSMA which requires mostly physical carrier sensing to operate and contrary to STDMA is not affected by hidden nodes in the considered scenario. Since our previous evaluation identified hidden nodes to have a severe influence on the coordination ability of STDMA we consider its severity as well as underlying cause in more detail in the following.

4.4.3 Impact of Hidden Nodes

Hidden nodes can have fundamentally different effects in a CSMA compared to an STDMA coordinated network. In case of CSMA, hidden nodes are no longer able to declare *CCA-busy* state and may start a simultaneous transmission which could interfere at potential receivers. For STDMA, a quite similar effect is possible where a hidden node selects the same slot to transmit in, but contrary to CSMA, hidden nodes could furthermore result in incoordination among nodes who are within each other's communication range, as has been visualized in Figure 4.4.

The focus in the following is hence to quantify the varying degree of how hidden nodes influence the coordination ability of STDMA contrary to CSMA at first hand and then evaluate its resulting impact on the achieved packet delivery ratio subsequently. All presented results are average values, based on five runs with different seeds for the random number generator. The resulting variance with five runs is already too low to be visible in the presented plots.

In order to determine how the coordination capability of both protocols is solely affected by the existence of hidden terminals, without having to consider varying ranges at which a nodes becomes a hidden terminal or the effect of packet error rate models, we employed a fixed range propagation loss model in a first step. The communication range is set to 500 meters, meaning that every node within this range can successfully receive a transmission if no other node within a distance of 500 meters transmits a packet itself.

In Figure 4.10 the resulting PLI for a scenario with a theoretical channel load of 50 % is depicted, depending on the ratio of hidden nodes to overall nodes and the MAC protocol being used. The number of vehicles that are within communication range of an evaluation node hereby stays the same in all setups and corresponds to 50 % channel load. A hidden node ratio of 1/2 denotes that the vehicle density stays the same over the whole scenario, whereas the vehicle density is reduced to half at distances larger 500 meters for a hidden node ratio of 1/3. In other words: From the perspective of a single node, a hidden node ratio of 1/3 denotes that out of all vehicles that can interfere my transmissions 1/3 is hidden to me.

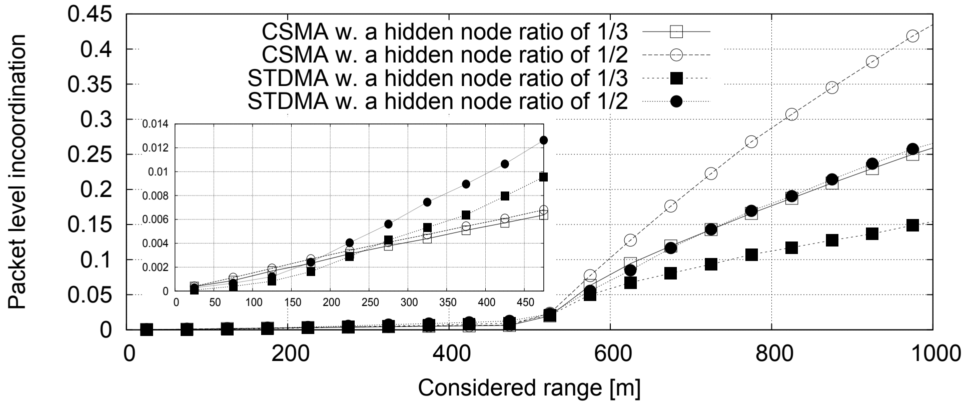


Figure 4.10: PLI with an estimated channel load of 50 % using a fixed range propagation loss model with a range of 500 m for a considered range up to 1 000 m and zoomed in to illustrate the range up to 500 m in more detail. Figure first published in [GMHS14].

Three general observations can be made in Figure 4.10. First, the overall PLI up to a distance of 500 meters is quite low for both protocols, concluding that both protocols are well capable of coordinating the channel within the communication range, even with the existence of hidden nodes. Second, the PLI drastically increases at distances larger than 500 meters, since CSMA is no longer able to carrier sense ongoing transmissions and STDMA is no longer able to extract reservation information originating from distances larger than 500 meters. Third, the more hidden nodes are present the higher the PLI gets for both protocols. Furthermore, when comparing the PLI for STDMA and CSMA in more detail, the following differences are observable:

- The PLI for CSMA increases drastically faster compared to STDMA at distances larger than 500 m. The reason therefore is that STDMA uses a slotted approach, where transmission times between different nodes are synchronized. An incoordinated transmission can thus only interfere with other transmissions taking place in the same time slot when using STDMA (full overlap), where with a non synchronized approach like CSMA an incoordinated transmission can interfere with transmissions starting any time from the first to last bit (partly overlap).
- In close range the PLI for CSMA linearly increases over distance as incoordination with CSMA within the communication range occurs if multiple nodes decide to transmit at the same point of time (e.g. by an equal backoff timeout, cf. [Mit12]).
- In close range the PLI for STDMA increases with an exponential trend. This increase can be attributed to hidden node issues, since we previously demonstrated that with the absence of hidden nodes and under the load that is considered here, there is rarely the chance of any incoordination. As we have previously discussed (cf. Figure 4.4), hidden nodes interfering with transmissions could result in missed re-reservation information and hence in incoordination even within the communication range. Due to its contagious nature this incoordination could further result in additional incoordination and so on and so forth.

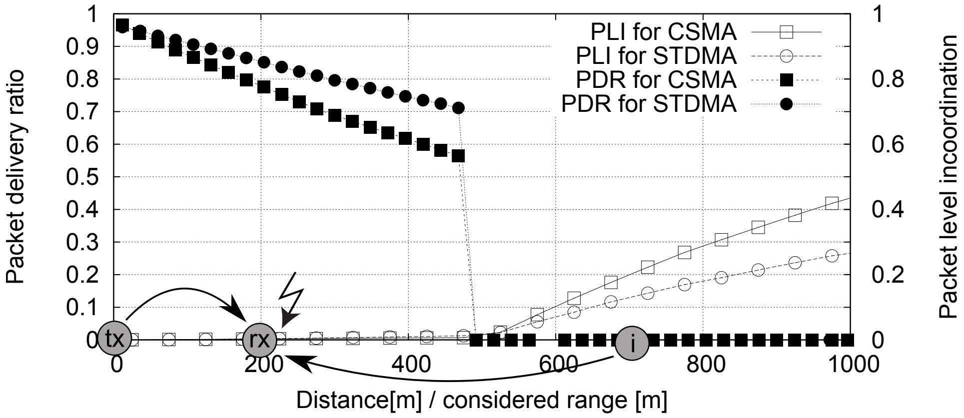


Figure 4.11: PLI and PDR for a scenario with a theoretical channel load of 50 %, a hidden node ratio of 1/2 and a fixed communication range model with 500 m. The PDR of node *tx* at a distance of 200 meters (represented by node *rx*) is influenced by all incoordination, occurring up to node *i* at 700 m, which can eventually lead to packet collision at node *rx*. Figure first published in [GMHS14].

> Hence, contrary to CSMA, the probability of incoordinated transmissions in close range increases with an increase of hidden nodes, since more nodes are able to interfere with reservation information exchanged within the communication range. This can be seen by comparing the PLI for a hidden node ratio of 1/3 vs. 1/2. Additionally, as the distance increases, the number of vehicles that are outside of the communication range (thus generally not coordinated), but still within interference range of a potential receiver increases, leading to an even greater increase of incoordination.

Consequently, for contrasting the PLI of CSMA and STDMA, Figure 4.10 can be divided into three different regions:

1. Up to a distance of ≈ 200 meters (for the given scenario) there is a higher probability of simultaneous packet transmissions by CSMA than hidden nodes interfering with transmissions and their contained reservation information when employing STDMA.
2. In the range from ≈ 200 meters to ≈ 550 meters the effect of hidden nodes interfering with reservation information leads to more PLI for STDMA than that of additional nodes starting their transmissions at the same point of time when using CSMA.
3. For larger distances (depicting the probability of hidden nodes being coordinated) the visible difference in PLI is due to the effect of slotted vs. non slotted approach, favoring STDMA over CSMA.

Figure 4.11 visualizes the resulting PDR in combination with the PLI for the scenario with a hidden node ratio of 1/2. Keep in mind that the PDR at some distance d is not only influenced by all incoordinations occurring up to distance d, but by incoordinations occurring up to a distance of $d + communication\ range$, as is depicted at the bottom of Figure 4.11.

For the first 25 m the PDR of CSMA is slightly better by 1 %, resulting from the marginal PLI benefit of CSMA within the communication range (cf. Figure 4.10). For larger distances the difference of slotted vs. non slotted approach is more decisive. The PDR does not reach 100 % even in close range, since any interference within the first 500 m hinders a successful packet reception. At distances above 500 meters no single packet can be decoded, as is expected with a fixed range communication model.

Even though previous insights were achieved by making use of the artificial fixed range communication model, its general trend does not substantially change under the power law communication model. The only visible difference is a slightly better coordination ability in close range for STDMA which is reasoned by nearby nodes still achieving a sufficient SINR to successfully decode a transmitted packet even if far away neighbors are interfering. We hereby refrain from visualizing its exact characteristic, but it is implicitly included in our following analysis, more precisely in Figure 4.13, with a different carrier sense configuration.

Influence of the carrier sensing range

Our last study revealed that as long as both protocols experience the same amount of hidden nodes, the slotted approach of STDMA results in better coordinating abilities at longer distances. However, CSMA's coordination mechanism primarily relies on being able to sense the channel, on the contrary STDMA primarily relies on being able to decode packets in order to extract reservation information. Consequently, the following questions are addressed next i) how does the PLI changes, depending on the relation between carrier sensing and decoding range or in other words how much benefit can both protocols gain by an extended carrier sensing range and ii) how does this influence the achievable PDR? For this study we employed the power law fading model. The threshold up to which a receiver is able to sync to a signal is set to -88 dBm, which equals a distance of 408 m. Please keep in mind that even when a receiver is able to sync to a packet it does not necessarily imply a successful reception, since the packet might still be dropped by the packet error rate model, due to non sufficient SINR. For this study the carrier sensing range is varied from 400 m to 1 000 m.

Figure 4.12 visualizes the PLI for varying carrier sensing ranges for CSMA and STDMA. As can be seen, CSMA greatly benefits from an increase of the carrier sensing range whereas the shape of the curve stays comparable to the one observed in Figure 4.10 (with a fixed range radio model). The increase of the PLI in close range can be explained by the fact that with a larger carrier sensing range the experienced channel load increases. An increase of channel load leads to more competition for the remaining free channel times, leading to a higher probability of simultaneous backoff timeouts. STDMA can in general also make use of sensing the channel as busy by blocking the same slot in the next frame, but in our setup no difference is observable when extending the carrier sensing range. However, as already mentioned and explained at the end of previous sub section, the PLI in close range (up to ≈ 200 m) drops significantly, compared to the results achieved with the fixed range communication model.

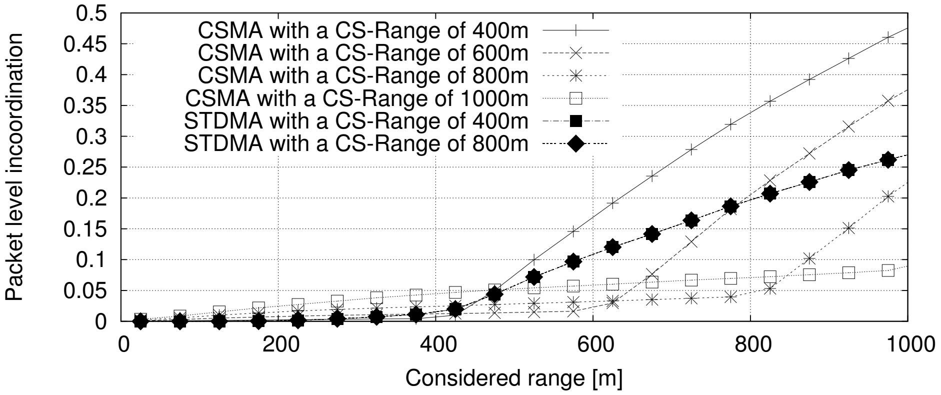


Figure 4.12: PLI for various carrier sensing ranges with a maximum decoding range of ≈ 400 m and a density of 85 vehicles/km. Figure first published in [GMHS14].

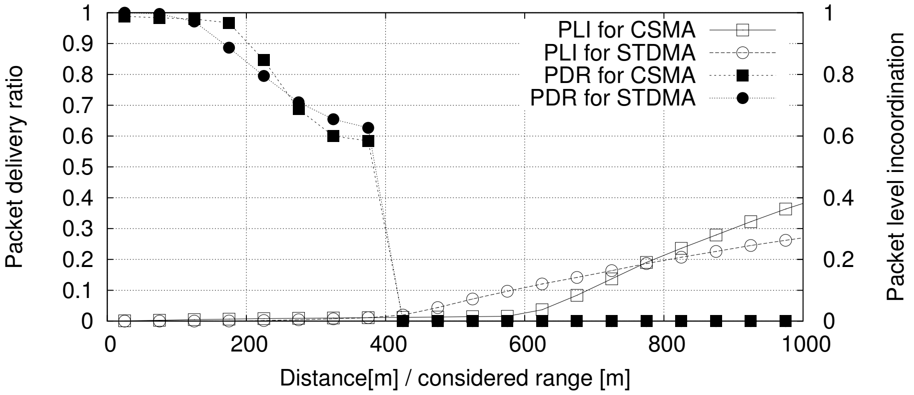


Figure 4.13: PLI and PDR for a CS-Range of ≈ 600 m (-91 dBm), a maximum decoding range of ≈ 400 m (-88 dBm) and a vehicle density of 85 veh/km. Figure first published in [GMHS14].

In Figure 4.13 the PLI for a CS-threshold of -91 dBm (≈ 600 m) and an RX-threshold of -88 dBm (≈ 400 m) is depicted in combination with the resulting PDR for CSMA and STDMA. The higher PDR for STDMA in ranges up to approx. 100 m is due to constantly lower PLI in ranges up to 400 m and incoordination occurring at larger distances only having minor effect on the SINR. CSMA has its strengths (regarding the PDR) in the range from 100 m to 250 m, since it benefits from an extended CS-range by being able to coordinate the channel up to larger distances. Due to its slotted approach the PLI changes again in favor of STDMA at distances larger than 750 m, resulting in higher PDRs for distances larger than 250 meters (cf. Section 4.4.3 for explanation).

4.4.4 Impact of Fading

In order to investigate to which degree the coordination ability of both protocols is influenced by temporary channel variations we employed a Nakagami distribution on top of the power law path loss model. Figure 4.14 depicts the resulting PLI without

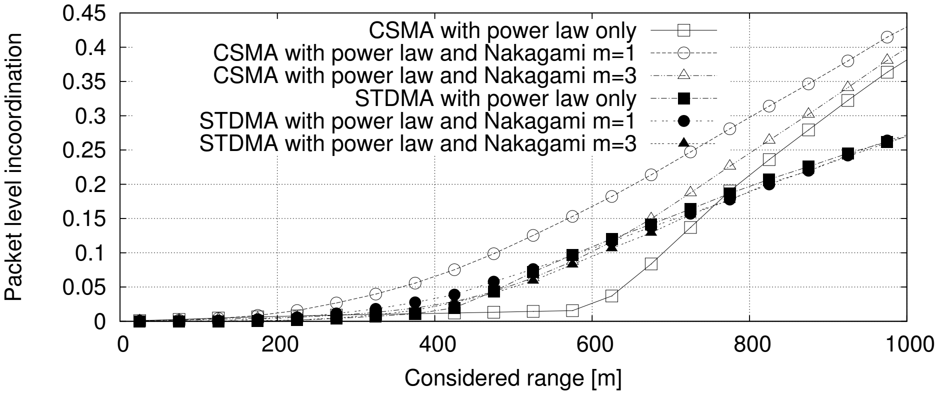


Figure 4.14: Impact of fading with varying intensity on the coordination ability of CSMA and STDMA with a CS-threshold of -91 dBm, an RX-threshold of -88 dBm and a vehicle density of 85 veh/km. Figure first published in [GMHS14].

any fading, with Nakagami $m = 1$, and Nakagami $m = 3$ for CSMA as well as STDMA. It is apparent that the coordination ability of CSMA decreases as the severity of fading increases. This is quite intuitive, since with more severe fading the probability increases that a node is not able to declare CCA-busy and starts transmitting itself, leading to an increased PLI even in close range. For STDMA no such clear distinction can be made. Despite varying fading intensities the PLI values hardly differ, where in close range the PLI slightly increases with more severe fading and in far ranges the PLI even slightly decreases, compared to non fading conditions at all. This can be explained by the fact that fading conditions lead to an increased number of packets in close range that cannot be decoded, consequently their reservation information are missed and this then leads to an increase in incoordination. As the considered range is increased this effect diminishes, as receivers which are outside of the designated communication range might still receive some packets once in a while. Since every STDMA-packet contains some additional reservation information (e.g., the next used slot within the same frame or for how long the current slot is being used) this information can then be used by the receiving station to decrease the likelihood of incoordinated transmissions.

Figure 4.15 depicts the resulting PDR for fading conditions with Nakagami $m = 1$ and Nakagami $m = 3$ for CSMA and STDMA. Compared to non fading conditions (see Figure 4.13) the PDR drops faster over distance, but successful packet receptions are still possible above the designated communication distance of ≈ 400 meters. With less severe fading ($m = 3$) the PDR up to a distance of 550 m is only marginally better for STDMA, whereas for larger distances both protocols do not show any noticeable difference. More severe fading ($m = 1$) is less detrimental for the reservation-based approach of STDMA, resulting in a difference of up to 5 % in PDR, due to the reasons that were given for the PLI explanation.

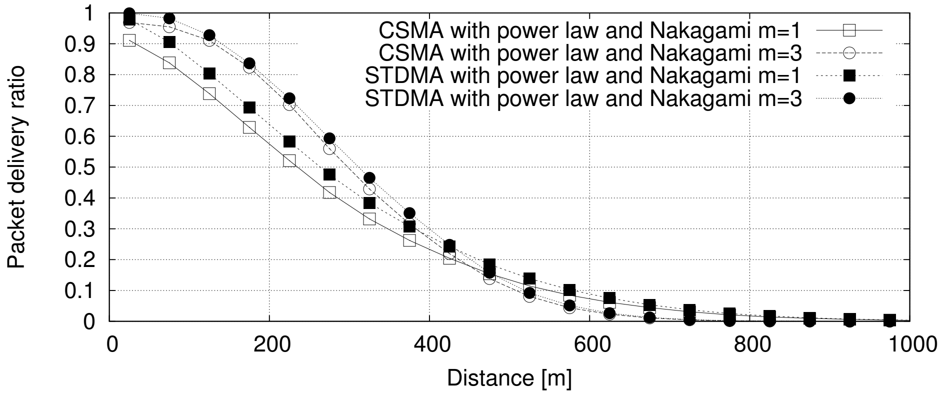


Figure 4.15: Impact of fading with varying intensity on PDR when using CSMA and STDMA with a CS-threshold of -91 dBm, an RX-threshold of -88 dBm and a vehicle density of 85 veh/km. Figure first published in [GMHS14].

4.4.5 Impact of Mobility

Our previous study demonstrated that STDMA, contrary to CSMA, can make use of occasional packet receptions, e.g., due to temporal fading conditions, by incorporating previously received reservation information in future channel allocations. While in such situations there is only a temporal change of the perceived vicinity, mobility of vehicles actually changes the neighborhood and hence the nodes which have to be coordinated, i.e., which have to adhere to a common slot allocation. Apparently, the reservation-based approach of STDMA is of disadvantage under these circumstances since reservations cannot spontaneously be adjusted and new occurring slot allocation collisions can be of contagious nature as previously discussed. For CSMA on the other hand no crucial impact has to be expected. Up to now, however, the microscopic impact of mobility on the coordination ability of STDMA has not been studied. In the following we hence first focus on (microscopically) understanding the roots behind incoordination due to mobility. Second, we quantify the severity of mobility on the coordination ability, but also on subsequent metrics, such as the packet delivery ratio.

Understanding the cause of incoordination

In order to understand how mobility affects the coordination ability of STDMA in comparison to CSMA we employed previously described highway scenario where two vehicle clusters are approaching, passing, and then moving away from each other. Within this scenario we analyzed the temporal trend of the packet level incoordination for considered distances of 100 and 300 meters. The resulting average incoordination level is visualized in Figure 4.16 which is based on 10 simulation runs with corresponding standard deviations visualized.

First of all, it can be observed that the average PLI is rather low overall, but clearly distinguishable between different points in time for both protocols. For CSMA, the highest PLI for both considered distances of 100 and 300 meters can be observed when both vehicle clusters are next to each other, which is simply reasoned by having the highest channel load in this situation.

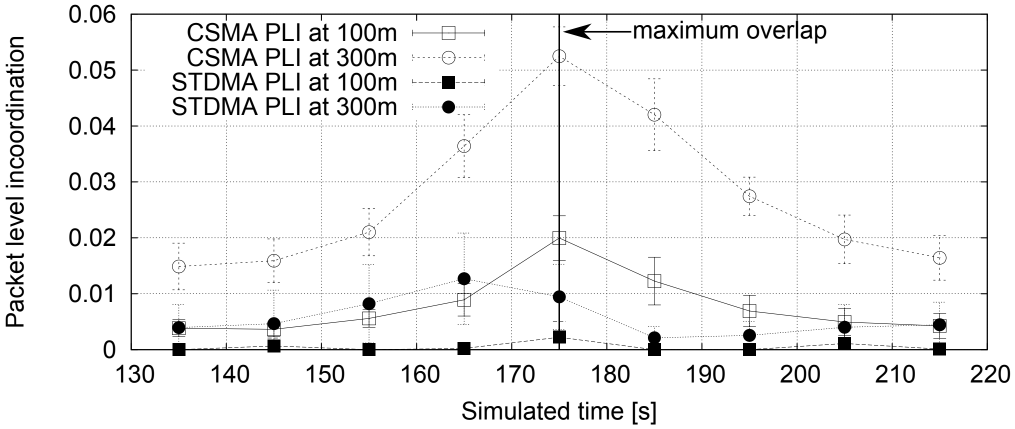


Figure 4.16: Temporal impact of mobility on the packet level incoordination in a highway scenario with two vehicle clusters approaching and passing each other. The PLI is evaluated at the two fixed distances of 100 and 300 meters. In total 126 vehicles generate a channel load of ≈ 75% with fading conditions according to Nakagami $m = 2$.

For a considered distance of 300 meters, the highest PLI when employing STDMA is reached prior to the maximum spatial overlap, namely when the two clusters encounter each other and previously *valid* slot reuse could now result in both transmissions being non-decodable due to stronger interference between the approaching vehicles. The statistical nature of these slot allocation collisions to emerge can be seen by means of the relatively high std. deviation at the time prior to the maximum overlap compared to afterwards. At the time of maximum overlap some of these new slot allocation collisions have been resolved and since all nodes are now within each other's communication range there are less hidden nodes, facilitating STDMA to find good slot allocations. It can be further seen that mobility aspects do not result in coordination issues for STDMA at close distances, as the considered distance of 100 m illustrates. Overall, it can be seen that CSMA and STDMA are challenged differently in previous scenario – CSMA with a high channel load at the time of maximum overlap and STDMA with having to resolve slot allocation collisions at the time of cluster merging.

Quantifying the impact of mobility

While previous analysis focused on identifying the microscopic impact of mobility on the coordination ability of STDMA and to understand the situations which are most challenging, the following evaluation quantifies how much of a difference has to be expected overall. For this purpose we employ the circular scenario where the vicinity of a vehicle continuously changes, i.e., previously uncoordinated stations entering the coordination range of a station, but being initially unaware of its slot allocations and to the same degree other stations leaving the designated communication area. STDMA is hence challenged by steadily having to resolve new emerging critical slot

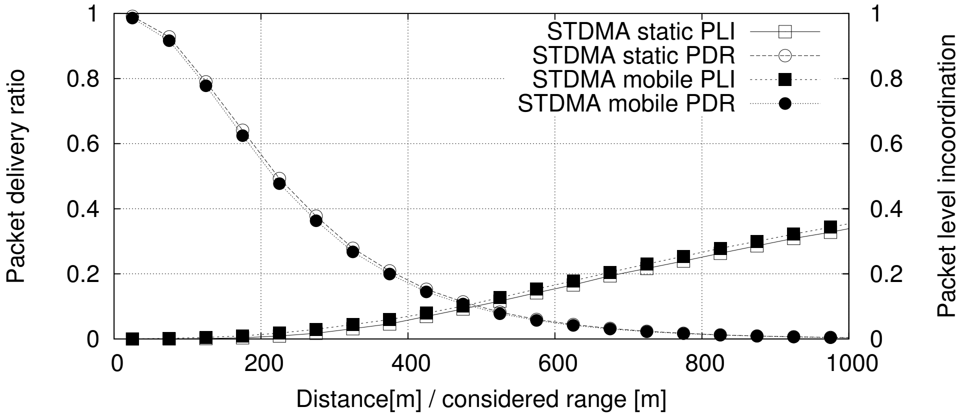


Figure 4.17: Comparison of PLI and PDR in the circular scenario with either static or mobile nodes. In total 629 vehicles are transmitting 10 packets per second each. Fading is modeled according to Nakagami $m = 2$.

allocation collisions. As a reference we employ the circular scenario layout, but without considering any mobility, i.e., vehicles are positioned static, but with the same vehicle density on the road. This approach enables to compare the direct influence of mobility on a multitude of metrics, with its impact on the PLI and PDR shown in the following.

As expected, there is barely any difference observable in the coordination ability of CSMA in a mobile compared to static environment which is why we refrain from visualizing it in the following. For STDMA, however, mobility poses a further challenge as previously discussed and leads to a slight increase of PLI and resulting drop in the packet delivery ratio as Figure 4.17 visualizes. A difference is hereby visible over the entire considered range, which is, however, not very distinctive and only has a minor overall effect on the PLI as well as PDR.

4.4.6 Comparison to CSMA

After having presented the strengths and weaknesses of STDMA in dealing with certain situations step-by-step in the previous subsections, we jointly consider all these effects in the following. By means of the packet delivery ratio and packet inter-arrival time we compare the achieved performance of STDMA and CSMA within the circular scenario.

Nowadays IEEE 802.11 receivers commonly employ so called frame capturing which enables to switch to a significantly stronger signal at the expense of dropping an already synched to reception. The reasoning behind this approach is that due to the new upcoming interference, the currently ongoing reception can anyhow not be decoded successfully in the end. Within CSMA coordinated vehicular networks this ability has been shown to be beneficial (cf. [SE10], [Wij11]), but is not included in the employed NS-3 simulator in its version 3.16. In order to ensure a fair comparison and incorporate currently common improvements we implemented previously described frame capturing, with the implementation being based on the work of Bingmann [Bin09] and the thresholds under which situations to switch to a stronger signal are adopted from the work of Schmidt-Eisenlohr [SE10]. One hereby basically distinguishes between

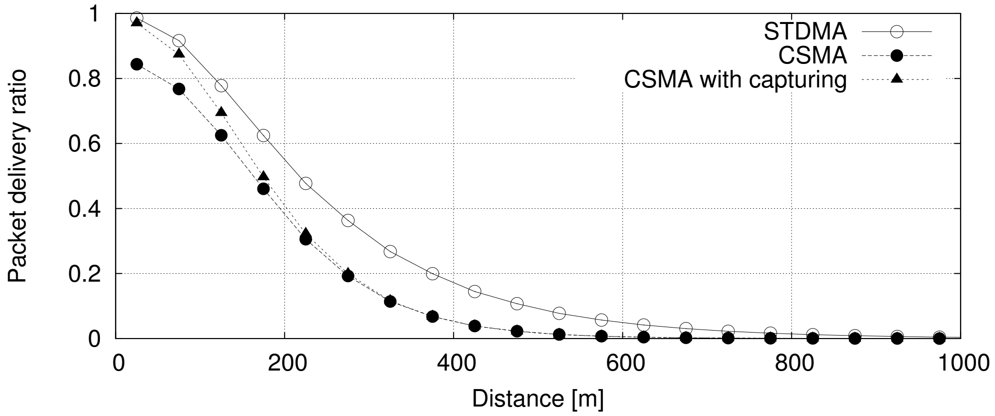


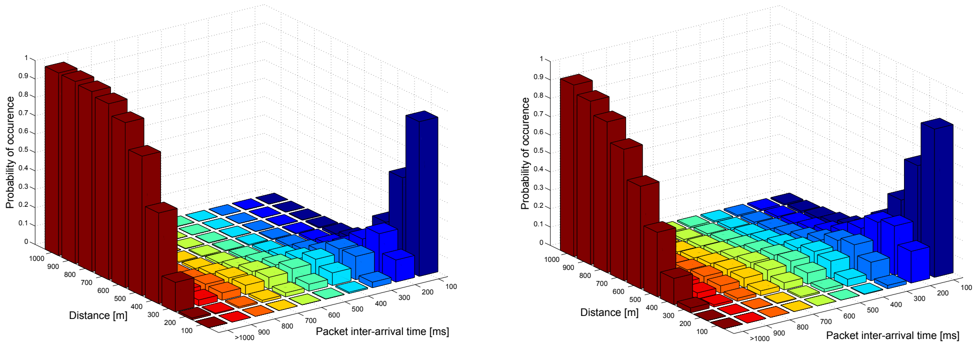
Figure 4.18: Comparison of the packet delivery ratio in the circular scenario with a total of 629 vehicles each transmitting 10 packets per second and a fading communication channel according to Nakagami $m = 2$ on top of the power law path loss. CSMA is evaluated with and without the capturing ability.

preamble and *full* capturing whereby the former only enables to switch signals as long as the current reception is still within its preamble phase. The required thresholds to switch are set to 5 dB while still within the preamble phase and 10 dB afterwards (in case full frame capturing is enabled). While in a CSMA coordinated network, improvements w.r.t. to the packet delivery ratio have to be expected, it is way less likely that a significantly stronger signal arrives at a receiver later than an already synched to and weaker signal when employing the synchronized STDMA approach.

Results on packet delivery ratio

A comparison of the packet delivery ratio as achieved by CSMA and STDMA in the circular scenario is visualized in Figure 4.18. For STDMA, the PDR corresponds to the curve shown in Figure 4.17 and for CSMA we employed two different configurations – once with frame capturing enabled and once without. For CSMA the impact of frame capturing is particularly visible at close range, which is quite apparent since otherwise the new incoming signal could not be a magnitude stronger compared to the signal which is currently being decoded, with no differences observable at larger distances.

The relative low packet delivery ratio at close range for CSMA without capturing capability can be explained as follows: Due to a high channel load in the considered scenario and a relatively low threshold up to which signal strength an incoming transmission is attempted to decode, stations are frequently busy decoding incoming transmissions, even if there is a high probability that *low signal strength receptions* are later being dropped by the packet error rate model. At the same time, stations which are close by might not be able to declare the CCA-busy state, reasoned by the existence of channel fading, and possibly start a transmission themselves. This transmission, even though it arrives at nearby stations with a signal strength a magnitude stronger than the one these stations are currently decoding, is not able to suppress the currently synchronized to signal at stations which do not possess capturing capabilities. As a result, there is a high probability that both incoming transmissions are lost.



(a) CSMA

(b) STDMA

Figure 4.19: 3D-histogram of the packet inter-arrival time distribution for several considered distances between transmitter and receiver when employing CSMA (left) and STDMA (right). Radio conditions were modeled according to a power law model with fading according to Nakagami $m = 2$ in the circular scenario.

For the sake of completeness it is also mentioned that we evaluated the impact of capturing on STDMA, but did not observe any perceptible difference which is why we refrain from visualizing it.

Within the considered scenario STDMA achieves an overall better packet delivery ratio across all ranges. While in close range the differences are only marginally, owing to frame capturing capabilities of CSMA, the synchronized approach of STDMA has an obvious advantage later on.

Results on packet inter-arrival times

In order to evaluate whether STDMA is more vulnerable to "block reception errors" that might eventually arise since two nodes selecting the same time slot are preventing their transmissions over a longer period of time we evaluated the packet inter-arrival time in a next step to incorporate a timely component. For all nodes within the considered scenario we measured the time between two successful packet receptions originating from the same transmitter and generated a 3D-histogram out of the obtained data. It should be noted that due to this binning, we abstract from precise inter-arrival times (influenced by the SI-length for STDMA or the channel access delay for CSMA) in favor of a clearer presentation.

Figure 4.19 visualizes the resulting PIAT distribution by means of a relative 3D-histogram for the circular scenario when being coordinated by CSMA (Figure 4.19a) and STDMA (Figure 4.19b). For a given distance, the distribution of the to be expected PIAT distribution is depicted. For instance, at a distance of 200 m in 56 % consecutive receptions from the same transmitter are successful, while in ≈ 27 % only every second reception is successful in an STDMA coordinated network (49 % and 22 % for CSMA). Packet inter-arrival times greater than 1 000 ms are hereby summarized in the last bin (1 000 ms). While this representation allows for an extensive overview of the packet inter-arrival times, it is hard contrasting the PIAT as achieved by CSMA and STDMA. For this reason, Figure 4.20 focuses on outlining differences by plotting the resulting

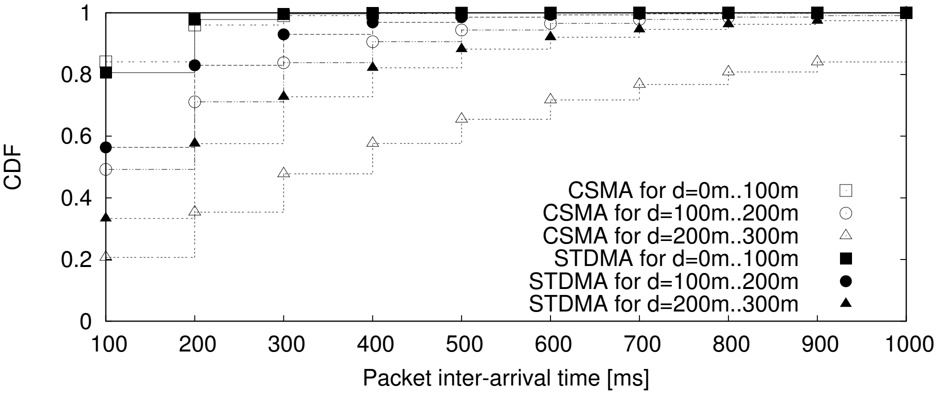


Figure 4.20: Resulting CDF for the PIAT analysis for three different considered ranges with power law path loss model with Nakagami $m = 2$ fading

PIAT CDF at selected distances. With the exception of a slightly higher probability for a PIAT of 100 ms at a distance of 100 m, the expected average PIAT for STDMA is slightly better than that for CSMA across all considered distances.

4.5 Conclusions

In order to address the stated research question, we extensively compared nowadays envisioned IEEE 802.11p random access based coordination scheme and its most promising competitor – the reservation based STDMA – to each other. Quite obviously, in order to answer the stated research question in its entirety, a comparison of more than two protocols might be necessary. However, given that these protocols are the most promising ones for a deployment in future inter-vehicle communication networks as well as that they employ fundamentally different coordination approaches, they serve as a valuable starting point. In addition, the results indicate whether already achieved impact assessment results (being based on a CSMA/CA channel coordination) or macroscopic modeling approaches, such as the one in Chapter 5, remain valid in case STDMA instead of IEEE 802.11p will in the future be employed for coordinating the channel access in inter-vehicle communication networks.

After presenting an overview over existing distributed coordination approaches for the wireless domain, we focused on pointing out that STDMA has not been subject to the same scientific consideration than CSMA. In particular, we identified that neither the impact of its parameterability is sufficiently understood nor a sufficient understanding of its strengths and weaknesses to cope with occurring situations is existent, which both are a prerequisite before considering STDMA as an alternative to the well understood IEEE 802.11 CSMA scheme.

In order to establish a solid foundation and identify potential crucial aspects within the protocol itself we provided a detailed protocol description of STDMA. For each of the four phases a station undergoes to during its lifetime, we illustrated the basic principles and pointed out existing turning knobs. Based on these protocol insights we subsequently employed a systematic approach to identify the situations in which STDMA is not able to achieve successful coordination. Basically, we identified that under perfect communication conditions either bad luck at startup or local slot allocation congestion can result in stations not being coordinated and concurrent transmissions to occur. Subsequently, we illustrated and discussed the underlying cause of how aspects which are existing within the vehicular domain, such as channel fading and mobility, could further result in STDMA not being able to successfully coordinate the channel.

After having identified potential causes of incoordination we employed a simulation-based assessment to quantify the likelihood of these situations to occur, but also to quantitatively assess how well STDMA in comparison to CSMA is able to cope with these situations.

First, we evaluated the impact of previously identified turning knobs and evaluated which parametrization yields to be most suited for a vehicular deployment. We considered varying load situations and concluded that STDMA is well capable of handling rather high channel load situations, but is more prone to individual incoordinated stations and severe channel conditions where ongoing transmissions cannot be successfully decoded, but only be detected. Based on these insights, we subsequently focused on evaluating situations and channel conditions which can basically prevent successful packet receptions, but at the same hand are rather common in a vehicular domain. In particular, we considered:

1. **Hidden node situations** which can result in packets being non-decodable which is a particular burden for STDMA, since it relies on being able to extract reservation information, contrary to CSMA which primarily relies on being able to sense ongoing transmissions. As a consequence, we identified a fundamentally different cause of influence, since hidden nodes are able to introduce new slot allocation collisions with otherwise coordinated nodes in an STDMA network. On the other hand, the synchronized approach of STDMA clearly results in less incoordinated hidden nodes and hence less nodes which can interfere with ongoing transmissions.
2. **Fading conditions** which can be quite severe in vehicular networks and temporarily change which vehicles are successfully able to decode incoming transmissions. While quite apparently the overall performance of both coordination schemes is affected, we identified that (severe) fading conditions are in general less detrimental for the coordination mechanism of STDMA compared to CSMA, since previously received reservation information can still be incorporated into future slot allocations, even if occasional packets are missed.
3. **The impact of mobility** on the coordination ability and overall performance of STDMA. We hereby identified that on a microscopic level the encounter of stations with a different view on slot allocations and the time it takes to resolve these is clearly visible, but its impact diminishes rather fast as the stations are approaching each other. On a more macroscopic level, the impact of mobility on the coordination ability and achievable packet delivery ratio remains visible for STDMA, but without changing the overall picture.

Our evaluation pointed out that the two fundamental different coordination approaches of CSMA (random access) and STDMA (reservation-based) likewise result in fundamental different strengths and weaknesses in dealing with particular situations. However, when assessing the impact on applications building on top of it, indicated by our packet delivery ratio and inter-arrival time evaluation, these differences diminish. While on the basis of the scenarios considered within this thesis, STDMA has a slight overall advantage in scheduling periodic transmissions compared to CSMA, no generally different application behavior has to be expected in the end. From the perspective of multi-scale modeling and with regard to a macroscopic modeling of medium access control aspects these insights hence justify to abstract from a particular realization.

Outlook

In the following we point out several fields of future research, primarily focused towards further assessing the performance of STDMA and assessing its suitability for a vehicular deployment. As our evaluation pointed out, the coordination approach of both protocols fundamentally differs by requiring that packets can be successfully decoded for STDMA or that they can solely be sensed for CSMA. Consequently, the exact characteristics of the radio channel and the receiver capabilities is decisive on how both protocols compare to each other. While we assessed its impact by means of a highway channel model, the overall results could differ in an urban scenario where there is generally a stronger decline of signal strength and hence potentially less hidden nodes or a different ratio of *known* vs. *hidden* nodes. Urban scenarios could furthermore be of special interest, since, as our evaluation pointed out, STDMA is challenged by having to resolve slot allocation collisions at the time of new vehicle encounters and this might be more problematic in an urban environment where communication ranges are lower and immediate warnings are necessary.

With respect to a deployment of STDMA in a vehicular domain, there are currently several unresolved issues which need to be addressed. Contrary to CSMA there is no support to assign emergency messages a higher priority and even though a mechanism exist to transmit additional messages at short notice, its performance has not be evaluated so far. In CSMA-based networks, power- and rate control mechanisms exist, which keep the channel load under a certain limit and hence try to ensure that the network is operated under stable conditions. For STDMA it might be worth considering i) what an adequate channel load is, depending on prevalent channel conditions, ii) whether existing mechanisms could therefore be employed, even though STDMA is less spontaneous in adjusting its transmission parameter settings compared to CSMA, or iii) how an appropriate power-/and rate control mechanism has to look like.

In this chapter we solely focused on decentralized channel coordination schemes and evaluated and contrasted the performance of two prominent, but fundamentally different representatives thereof. Advances in receiver capabilities or the emergence of new decentralized coordination schemes might, however, make it necessary to reevaluate the insight that one can abstract from a particular MAC realization for a macroscopic inter-vehicle communication modeling approach. As future work it might also be worth considering whether centralized TDMA approaches exist, which could, for instance, be employed for platooning applications, and which difference have to be expected in that case.

5

Information Dissemination

In this chapter, we are addressing the research question of whether and to which degree the beaconing-based dissemination of information in an inter-vehicle communication can be modeled macroscopically. Modeling the information dissemination in nowadays simulation studies is commonly done by individually considering each and every packet exchanged within the considered network. At each individual vehicle the received information is then put together and a local view on the surrounding is generated. While this approach is based on what is actually going on in reality and can produce rater accurate results, it prevents a scaling up for desirable large-scale assessment due to excessive communication simulation overhead. While there are different motivations and consequently different means of information dissemination in inter-vehicle communication networks we solely focus on beaconing-based information dissemination in the following. Consequently, the focus is on modeling how information, such as decentralized collected floating car data, is disseminated and we neglect how event messages, e.g., the warning of a broken down vehicle, are disseminated by means of multi-hop communication.

Within this chapter we first present a general concept and framework which allows to abstract from an individual modeling of exchanged packets, but at the same time still enables to derive individual views of nodes, describing a vehicle's awareness on its surrounding. Second, we present an information-centric model which can be employed in previously presented framework and allows to determine the dissemination delay between two arbitrary nodes in an inter-vehicle communication network.

Section 5.1 motivates the importance of being able to appropriately model the information dissemination in inter-vehicle communication networks and points out why currently employed approaches are not suited for addressing research questions which require large-scale considerations. In Section 5.2 related work is presented, on the one hand, with respect to the aspects which have to be considered for an appropriate modeling of information dissemination and which approaches are existent to do so other than the simulator coupling approaches, which have already been presented in Section 2.5.1. On the other hand, we focus on presenting related work with respect to information dissemination protocols and the characterization of information delay in inter-vehicle communication networks. Section 5.3 then presents a novel approach which allows to employ multiscale models for the modeling of information dissemination in inter-vehicle communication networks. Section 5.4 picks up this approach and develops an information-centric light-weight modeling approach which enables to determine the dissemination delay between two arbitrary nodes without having to model the exchange of millions of packets, as is done nowadays. The model is based on an extensive simulation study which was conducted to characterize information dissemination delays in inter-vehicle communication networks under a multitude of varying conditions. Section 5.4 hence further presents selected results, indicating the impact of certain aspects on the speed of information dissemination as well as on their interdependencies. The applicability of the proposed approach is evaluated and discussed in Section 5.5 by contrasting it to a commonly employed fine grained packet-based simulation approach. Finally, Section 5.6 summarizes this chapter.

Parts of this chapter have been previously published in [GSEMH11] and [GMH12].

5.1 Motivation

Information dissemination is in general considered as the way information is distributed in a network. Within the context of inter-vehicle communication networks this dissemination of information can generally occur on the one hand by means of communication, e.g., a vehicle broadcasting or forwarding a warning message, on the other hand information is also solely disseminated by means of mobility. For characterizing information dissemination within inter-vehicle communication networks one is hereby typically interested in i) how detailed and accurate information can be disseminated within the network, and ii) how outdated this information is when arriving at some distant vehicle.

The characteristics of information dissemination hereby significantly determine the overall suitability of the envisioned inter-vehicle communication system as well as its impact on the road transportation system. For this reason, system architects as well as traffic engineers are in particular interested in having an answer to the question of "which (additional) information is available to the driver/application due to vehicular communication?". Since modeling the information dissemination is hence such a critical aspect for assessing the benefit of vehicular communication on our road transportation system the networking community developed so called *integrated simulation tool sets* that combine the multiple aspects of intelligent transportation systems, namely *application*, *communication* and *traffic*, into one evaluation and assessment framework. While these approaches have done a great service for understanding and assessing the impact of vehicular communication in small-scale and typically with a focus on communication aspects, existing vehicular communication simulators do not scale beyond networks with more than a few thousand vehicles. The two main reasons are i) synchronization overhead which arises due to the coupling of simulation models, and ii) the focus of network simulation models on individual packets, instead of providing insights w.r.t. "which information is available to the driver at which point in time". Based on this principle, modeling the local view of a vehicle requires the simulation of millions of packets being exchanged within the network. As a result, this approach does not scale well and it is not possible to simulate large-scale scenarios that represent a single state or a whole country and which traffic engineers or decision makers are interested in.

In order to facilitate large-scale assessments we hence propose to shift the paradigm away from modeling the exchange of packets towards modeling the availability of information directly. Such an information-centric modeling approach can help i) to facilitate the interactions between communication/networking experts and traffic/application engineers, ii) to improve the scalability of corresponding simulations, and iii) to widen the scope of problems that can be addressed via simulations.

One possibility to realize an information-centric modeling approach is presented in Section 5.3 which makes use of the fact, that in a simulation environment, contrary to reality, there is a single instance (the simulator) which possesses god view. On that basis, the local views of vehicles at an arbitrary point in time can be derived from this global view by altering it w.r.t. to level of detail, accuracy as well as delay that the information has undergone to before arriving at the designated vehicle. A prerequisite for an appropriate information-centric modeling is hence the availability of models which are able to describe how information is aggregated or delayed as it is propagated through the vehicular network. Creating these models is particularly challenging, since i) road networks can be arbitrary shaped, and ii) there are plenty of aspects which can have a significant influence on the information dissemination characteristic, such as existing communication conditions, the employed dissemination scheme or the mobility of the vehicles themselves. In order to address the first challenge we propose a modeling approach which decomposes an arbitrary road network into elementary blocks with known information dissemination delay characteristic. The second challenge is addressed by performing an extensive simulation study to characterize the time delay of beaconing-based data dissemination in inter-vehicle communication networks since existing analytical models only incorporate a subset of previously discussed influencing aspects. This characterization is then used for model building of elementary building blocks for the proposed modeling approach, in particular for a straight road of arbitrary length for highway, rural, and city scenarios as well as for an intersection.

5.2 Related Work

As previously discussed, modeling of information dissemination plays a central role for assessing the impact of inter-vehicle communication since it characterizes how accurate and outdated information is when being distributed in an inter-vehicle communication network. It hence determines which information is available to a communication-based vehicular application and in a subsequent step is decisive on whether appropriate advices can be given to a driver. An appropriate modeling of information dissemination is particularly challenging since it requires the incorporation of a multitude of aspects. In Section 5.2.1 we first give an overview over i) aspects which have to be considered for the modeling of information dissemination and ii) which approaches have previously been employed for doing so. Section 5.2.2 then focuses on related work w.r.t. the characterization of information dissemination in vehicular networks.

5.2.1 Modeling of Information Dissemination

In an inter-vehicle communication network the two primary means of information dissemination are i) mobility and ii) communication. Information which is known to one subject, e.g., the amount of free parking spaces, is already disseminated, solely by being *carried around* by the vehicle, but in the spirit of inter-vehicle communication is only reasonable if being communicated to other subjects as well. Communication hereby on the one hand extends the awareness range by making the information available to a wider range of vehicles and on the other hand can tremendously accelerate the speed at which information is being disseminated. The rate at which information is being disseminated is hereby decisively influenced by the *network connectivity*, which itself depends on the localization of vehicles (mobility aspect), but also on communication aspects, such as between which vehicles a successful communication can take place. Consequently, an appropriate modeling of information dissemination has to incorporate at least these two aspects and is nowadays often realized by employing dedicated simulation models which are then coupled in integrated simulation tool sets (cf. Section 2.5.1).

While this approach allows to deploy validated models and has done a great job for bringing every aspect together, hence facilitating impact assessment of inter-vehicle communication, it does not scale well for large-scale assessment as has previously been discussed.

The existence of a fundamental understanding of the characteristics of information dissemination in a respective network greatly facilitates the ability to directly model the availability of information in this network. As the authors of [GEK⁺11] and [ASH⁺08] have pointed out, this is per se no easy tasks in mobile ad-hoc networks. Contrary to Shannon's link-level information theory, information dissemination in a wireless ad-hoc network is influenced by many more parameters and so far no general answers on the subject of achievable throughput or capacity can be given. Nevertheless, first studies exist on characterizing how information is disseminated within a wireless ad-hoc network which do not address the fundamental question, but are able to address partial aspects of it. Studies which focus on quantifying information dissemination in inter-vehicle communication networks are presented in the following Section 5.2.2.

The usage of packet-based communication models and the consequent necessity to simulate each and every exchanged packet within the network results in communication aspects having the dominant share of the overall complexity and runtime requirement of the simulation. As the authors of [KSEH+07] have pointed out, it already takes a considerable amount of runtime to solely simulate communication aspects in a rather small-scale vehicular scenario, which is in the order of 20 minutes for a vehicle density of 400 veh/km, 100 seconds simulated time, and only one packet being transmitted per vehicle per second. It is easy to imagine that if not only a few hundred vehicles, but hundred of thousands of vehicles and a simulated time of several hours is of interest, a packet-based simulation approach is not realizable, even if considering potential speedups, e.g., due to Moore's law [Moo65], distributed computing ([BDFBC06], [PR11]), or GPGPU acceleration [YA14]. In addition, there is the inherent technical requirement of simulator coupling approaches to exchange control, synchronization, and data messages between the dedicated simulation models. This is typically done over expensive UNIX or TCP sockets and further limits the realizable simulation studies.

To address existing runtime performance issues, Killat et al. [KSEH+07] dismissed a coupling of simulators and instead employed the principle of *hybrid simulation* [Sch78]. Instead of modeling the communication aspect through discrete event-based simulation, Killat et al. developed a mathematical – but statistically valid – model of the packet reception probability and integrated it into a vehicular traffic simulator. With this approach, control overheads that are necessary for the coupling of standalone simulators, and the slowdowns due to highly detailed communication models, are avoided. However, their model is still based on the exchange of individual packets and is in general not suited for answering the question of "which information is available to which driver at which point in time" since it abstracts from the majority of packets, including their contained information, in favor of better runtime and scalability. The model has been integrated into an evaluation framework termed vtSim [BFB10] which focuses on a standardized description language for scenarios and ITS use cases in order to be able to simulate scenarios by multiple simulators or at multiple scales, and to compare the generated results. To the best of our knowledge no communication modeling approach is existent which is related more closely to our approach, w.r.t. enabling larger simulation studies by leaving expensive packet-based simulation approaches behind. For a more general overview of simulation tools which are employed nowadays for the simulation of vehicular ad-hoc networks we refer to the survey of Stanica et al. [SCB11b].

The employed dissemination protocol is another major influencing factor which determines the characteristic of information dissemination within an inter-vehicle communication network. A multitude of approaches and specific protocols have hereby been proposed in recent years, ranging from simple flooding techniques (e.g., [TWB+07], [WHF+07]), geocasting (e.g., [MWH01], [ZZC07], [FWK+03]), over request and reply principles (e.g., [SSHN07]), publish/subscribe patterns (e.g., [LM07]), periodic multi-hop beaconing approaches (e.g., [WFGH04]), to store-carry forward mechanisms (e.g., [WER05]) which allow to bridge connectivity in partitioned networks. Several of these principles have further been combined for more advanced protocols. An inevitable feature of beaconing-based information dissemination protocols is the ability to aggregate data as it is disseminated along the way as Scheuermann et al. [SLRM09] have proven. They point out that due to the limited bandwidth of the communication system, information has to be aggregated inversely proportional to the distance d between information source and the receiving destination by at least $1/d^2$. Depending on the intended use case of the disseminated information several aggregation schemes have been proposed: blind averaging, timestamp-based averaging (e.g., [XB06]), road-segment averaging (e.g., [WER05]), or hierarchical approaches which aggregate over similar vehicles (e.g., [NDLI04]) or areas (e.g., [CGM06]). Since it is not the objective of this chapter to develop yet another protocol or compare their performance, we omit a further introduction and refer to the survey of Lochert et al. [LSM10].

Within this thesis, solely the dissemination process between vehicles is considered and we do not incorporate the effect of road side units (RSU). It should, however, be noted that the existence of RSUs which are connected to a backbone can have a significant beneficial effect on information dissemination in vehicular networks. Information which is received by one RSU can nearly instantaneously be distributed to other RSUs and be retransmitted from there on. Lochert et al. [LSW+08], for instance, considered how RSUs can optimally be positioned and concluded that already a small amount of RSUs are sufficient to considerably support the information dissemination.

5.2.2 Characterization of Information Dissemination

Wischhof [Wis07] was among the first to develop a model that describes the speed of information dissemination as a function of the transmission range, the traffic density, and the average speed of all vehicles. The model is applicable to straight roads and to fully as well as to partially connected networks. Their closed-form expression is based on a set of simplifying assumptions: unlimited bandwidth (i.e. no bandwidth constraints), no transmission errors (i.e. no channel fading), no packet collisions, optimal forwarding decisions, a constant per-hop delay (i.e. received information is always forwarded after a fixed time delay), and no mobility during the dissemination process.

In 2009, Wu et al. [WFRH09] took up this effort and developed an analytical model that additionally incorporates mobility of vehicles (i.e. topology changes) during the dissemination process. Similar to the work of Wischhof in [Wis07], the dissemination process is divided into *forwarding phases* in which progress is achieved due to multi-hop relaying, and *catch-up phases* in which progress is achieved due to mobility of vehicles. While this is an improvement over [Wis07], the authors still assumed unlimited bandwidth, no packet collisions, no channel fading, and optimal forwarding. Just recently, Hassan et al. [HAR15] focused on improving the model of Wu et al. [WFRH09] by modeling the catch-up process in a closed form.

Wolterink et al. [WHvdB12a] contributed an analytical model that describes the stochastic distribution of the dissemination delay (the per hop delay, the hop length and the position of the i-th forwarder) as a function of the transmission range, the node density, and the beaconing rate. Their model assumes a beaconing-based dissemination approach, i.e., every vehicle transmits locally collected information periodically and piggybacks received information from neighboring vehicles. However, the model does not account for mobility during the dissemination process. Further, only fully connected networks were considered, hence, scenarios in which part of the progress has to be achieved using store-carry and forward mechanisms are not covered. Inter-vehicle distances were assumed to be fix and equally distributed, but this assumption was later changed to exponentially distributed inter-vehicle distances in their subsequent publication [WHvdB12b].

Besides previously mentioned studies there are a multitude of similar approaches existing in the literature which are briefly sketched in the following and which generally either focus on i) the feasibility of information dissemination in inter-vehicle communication networks (which was of particular interest in early years) or ii) on obtaining a fundamental understanding on how certain aspects, such as mobility, influence the speed of information dissemination.

Studies with the primary focus to evaluate the general suitability of inter-vehicle communication networks to disseminate information over multiple hops were, for instance, conducted by Yang et al. [YR05] which evaluated the influence of the communication range as well as market penetration rate on the feasibility of information dissemination, i.e., the maximum achievable propagation distance by means of simulation studies. Wang [Wan07] analytically modeled the information dissemination process and focused on understanding relationships between communication distance, vehicle penetration rate and maximum dissemination distance. Jin et al. [JR10] provided a recursive model to determine the multihop connectivity in an inter-vehicle communication network which allows to predict over which distance a sole communication-based dissemination is possible, given an arbitrary vehicle distribution. These studies have in common that there is only a marginal consideration of mobility effects, i.e., the network is assumed to be static during the dissemination process and rather simplistic assumptions are made with respect to communication conditions, e.g., a fixed distance is assumed up to which a transmission is always successful and no interference between multiple nodes is being considered.

Both of these shortcomings have motivated further work. For instance, the authors of [WLJ09] compared the achievable throughput in an inter-vehicle communication network if modeled analytically to that if simulated by means of NS-2 simulations. In particular, they identified that under high load channel conditions, the analytical model is too optimistic, since interference due to simultaneous occurring transmissions are not considered. Schönhof et al. [SKTH06] focused on the impact of more realistic traffic movement/situations on the speed of information dissemination and particularly evaluated whether "upstream message propagation" – dissemination of information in the opposite direction of travel – is feasible.

Agarwal et al. [ASL08] employed an analytical modeling approach to determine lower and upper bounds of information dissemination speed and demonstrated its sensitivity to the traffic density (of equipped vehicles) and the vehicle speed. Wang et al. [WLLR14] focused on an analytical consideration of the information dissemination speed under low penetration rates, e.g. 2 %, in order to evaluate whether information dissemination is reasonable possible, even in an early deployment phase. Zhang et al. ([ZMA10], [ZMA14]) focused on analytically modeling and understanding the impact of time-variant vehicle speeds and found it having a positive effect on the overall speed of information dissemination. Their study is again based on several simplifications, for instance, the assumption of a unit disk communication model. Just recently, in 2015, Du et al. [DD15] published a model which incorporates a SINR reception model and hence allows to consider the impact of communication conditions, such as transmission power or interference of simultaneously occurring transmissions in more details, compared to previous studies. Their numerically achieved results are furthermore compared to real-world measurements performed on one-way and two-way road segments in the US.

To summarize, based on the multitude of developed models and the varying research focus in the related work one can identify that there is a strong interest of characterizing information dissemination, in particular the dissemination speed, achievable dissemination distance, as well as information penetration rate in vehicular networks. This interest can be justified by the desire for a fundamental understanding of possibilities as well as limitations of information dissemination in vehicular networks. It determines the suitability of the overall envisioned communication system, including developed protocols, and reveals upon which data basis vehicular applications have to take decisions that might impact the road traffic in the end. A direct modeling of the availability as well as quality of disseminated information is hereby not only of interest for application design, but in a subsequent step also enables impact assessment studies in large-scale scenarios, which are not feasible nowadays.

While the studies and analytical models which have been discussed in this section allow to better understand or derive certain fundamental properties of the information dissemination process in vehicular networks, they are not necessarily suited as a basis for simulation studies. The reason for this are simplistic assumptions, primarily of traffic or communication conditions, but also the absence of a model which considers the combined influence of road network layout, mobility, as well as communication aspects. Driven by the stated research question of evaluating whether it is possible to macroscopically model the dissemination of information in inter-vehicle communication networks we hence conducted an own extensive simulation study, incorporating all these aspects, and developed an empirical model for the speed of information dissemination out of this data which is presented in Section 5.4.

5.3 Information-Centric Multiscale Modeling

In the context of inter-vehicle communication networks, we consider an information-centric modeling approach as one which *directly models the availability of information*, e.g., the local view of a vehicle on the perceived traffic situation, and not the exchange of packets between vehicles in order to establish this information. As previously discussed, such an approach could facilitate large-scale assessments which are not feasible nowadays.

5.3.1 Concept

While nowadays employed simulation tools recreate what is actually going on in reality where information is only available in a distributed way, it is possible in a simulation setting to directly access every data available and stored at the simulation tools. For example, it is of ease for the traffic simulator to calculate the vehicle densities or average velocities on each and every road based on the global knowledge it possesses without having to expensively "bring together" this information first. The challenge which then arises is to find a projection/model which appropriately represents how information is distorted in time and space as it is being disseminated through the network. Quite obviously, nowadays employed event-driven communication models could be employed for this purpose, but in this case nothing is gained with respect to required runtime and resulting scalability. However, following the idea of hybrid and multiscale simulation approaches, it appears feasible to employ projections which are easy to compute and still cover essential features of the communication and information dissemination process. An appropriate projection hereby has to incorporate that the (distorted) local view of an individual vehicle usually differs from the global view by having only

1. a *limited* view on the vicinity and not on the whole network
2. *outdated* information with an age that is increasing for *information* sources located further away
3. *inaccurate* data, since i) not every information/packet can be successfully forwarded, e.g., due to occurring interference, and ii) information has to be aggregated along the way, as is pointed out by Scheuermann et al. [SLRM09].

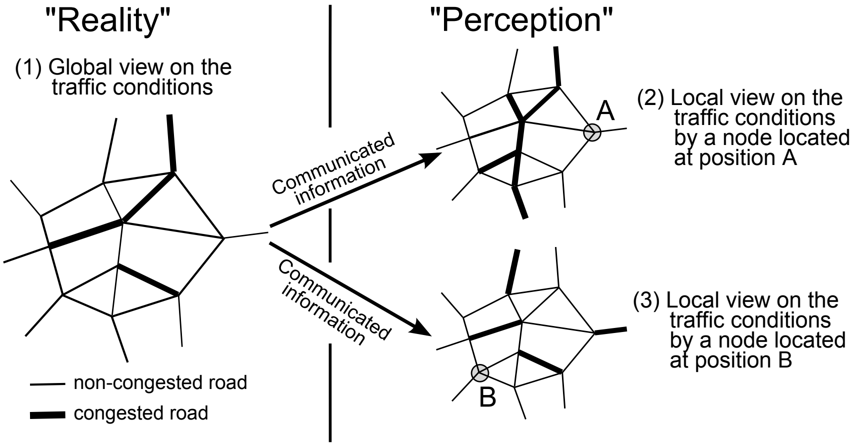


Figure 5.1: Global versus local view on the traffic situation in an exemplary scenario: the traffic simulator has a perfect knowledge on how the *simulated reality* looks like and therefore has a global view on the traffic conditions. Individual vehicles perceive the conditions through communication and obtain a local and location-dependent view – a delayed and distorted copy of the global view. Figure first published in [GSEMH11].

As a consequence the local views of individual vehicles may differ among each other and also in comparison to the global view, as depicted in Figure 5.1. Hence, the basic challenge behind information-centric modeling is to find an appropriate projection from the available global knowledge to the local view of an individual vehicle.

In order to be able to implement such a projection, we propose to extend existing vehicle traffic simulators and to use their global knowledge about the traffic conditions as a starting point for the projection. Based on the existence of this knowledge, the projection is then only a three-stage process, as depicted in the architectural overview of Figure 5.2:

1. **Extraction** of *traffic snapshots*
2. **Storage** and aggregation of these snapshots
3. **Filtering** of the snapshots to derive a local view

Extraction of existing global knowledge out of the used traffic simulator. The data that has to be extracted and the necessary granularity has to be determined according to the object of study. Depending on the considered use case/study it might be sufficient to only extract certain elements or reduce the accuracy of the extracted data. For the extraction of relevant data an interface between the traffic simulator and the information-centric communication model has to be defined, which allows the data exchange between both components.

Storage of extracted data. Since information dissemination in vehicular communication networks, based on dedicated short range communication (e.g. IEEE 802.11p), can take a considerable amount of time (up to several minutes in large-scale scenarios) the view of an individual vehicle on areas far away is hence generally outdated. The storage of historical data, however, supports the correct representation of historic outdated data and is thus enabling appropriate temporal modeling.

Filters are the most crucial part of the information-centric modeling approach. They are responsible for the projection of the traffic simulator's global view to the local view of a vehicle. To this purpose the extracted global snapshots have to be adapted and/or combined to derive time- and position-dependent local views for each vehicle. In order to derive accurate local views, a filter should consider lower layer details as accurate as possible, e.g., packet collisions, channel fading or environment characteristics. Hence, one option to implement such a filter would be the usage of traditional network layer simulators as it is currently done in nowadays simulator coupling-based approaches. However, with this option the runtime performance will not be as efficient as desired. Instead, we believe that such filters should be based on statistical valid models that have been derived either from accurate simulation results or from empirical data collected during field operational tests.

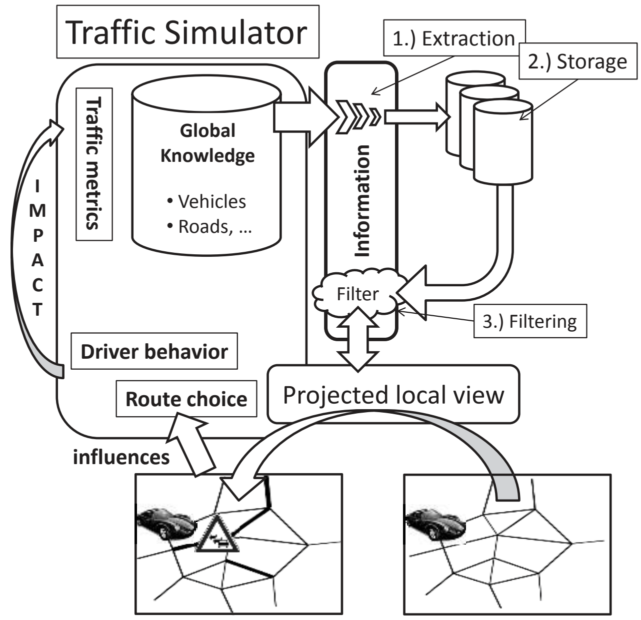


Figure 5.2: Architectural overview of the proposed information-centric modeling approach which consists of three building blocks. Figure first published in [GSEMH11].

5.3.2 Discussion

In order to evaluate the feasibility of previously presented modeling concept we implemented a proof-of-concept which offered a basic functionality of every necessary aspect. In particular, we were interested whether the *extraction* and *storage* of traffic related information poses a major challenge for the realization of such an approach. On the basis of one specific use-case, namely the dissemination and determination of *average velocities on roads* over floating car data, we implemented a prototype and attached it to the well known microscopic traffic simulator VISSIM[1].

By making use of existing interfaces we were able to continuously extract the relevant data, with a temporal resolution which corresponds to the fixed time increment of the traffic simulator, which is nowadays usually set between 0.1 and 1 second. Since this granularity is commonly not needed and in order to save storage capacity we aggregated the extracted data in a second step, e.g., with a granularity of 10 seconds. The sole runtime requirement of these two steps i) extraction and ii) storage including aggregation accounted for less than one second in a typical sub-urban scenario with up to 2 000 vehicles and 1 000 simulated seconds on a common workstation with a 2.5 GHz Quad Core and 4 GB of RAM. In comparison, the overall traffic simulation runtime accounted to 70 seconds.

The filter functionality was based on the work of Wischhof et al. [WER05] and solely modeled the information delay that the information "experiences" on the way between an information source and potential receivers. This realization is hence

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[1] `http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/` [last visited in December 2015]

suited for use cases where the availability of information is just a matter of time (e.g., optimized route guidance by decentralized floating car data), but it is conceivable that it can be extended to use cases where information is only available and necessary in a limited spatial extend. By making use of such an information-centric modeling approach, the focus of the simulation study is shifted from analyzing the impact of packet receptions on communication protocols or applications towards assessing the influence of vehicular communication, in particular the information provided by vehicular communication, on vehicular traffic. In addition to currently employed simulation tools which are in general focused to model dedicated short range communication, e.g., IEEE 802.11p, and do not support the simulation of hybrid networks, an information-centric modeling approach is well capable of integrating multiple dissemination means, e.g., to consider how cellular networks can support the information dissemination in vehicular networks.

While the implemented prototype demonstrated the general feasibility of the proposed information-centric modeling approach, it became apparent that i) the extraction and storage of traffic snapshots does not pose a problem, but ii) an appropriate data basis was missing for deriving accurate and easy to calculate filter functions. Hence, we subsequently focused on developing an information-centric model which is able to efficiently model the dissemination delay in arbitrary road networks. Since the proposed modeling approach relies on known delay characteristics for selected building blocks we performed a comprehensive study to characterize the combined impact of a multitude of influencing aspects on the speed of information dissemination in vehicular networks.

5.4 Characterization and Modeling of Dissemination Delays

In this section we propose an information-centric modeling approach to describe the time delay of beaconing-based data dissemination in inter-vehicle communication networks. It is based on the analogy of a construction kit with elementary, connectable road shapes (or “blocks”, e.g., a straight road, an intersection, or similar). The proposed concept supports arbitrary road network layouts, is extensible, and allows to improve the accuracy (and statistical correctness) of blocks over time. We provide a delay characterization for two elementary blocks of the construction kit: a straight road of arbitrary length for highway, rural and city scenarios, as well as an intersection. These building blocks are based on an extensive simulation study and incorporate application, communication, and mobility related aspects.

First, the modeling concept is presented in Section 5.4.1, second, the methodology as well as exemplary results of the conducted simulation study, which serve as a basis for the proposed model, are presented in Section 5.4.2. These results are further taken up in order to identify and discuss the sensitivity of the speed of information dissemination in inter-vehicle communication networks.

5.4.1 Construction Kit Based Modeling Approach

The proposed dissemination delay modeling approach employs the *divide and conquer* principle by means of a simple construction kit: instead of evaluating the road network completely, the network is decomposed into elementary *blocks* which are evaluated independently from each other and added together in the end. The general idea behind this approach is illustrated in Figure 5.3: In order to determine the dissemination delay from the source position A to the destination position B, one simply decomposes the overall road network into basic building blocks with known delay characteristic, and sums up all intermediate delay values on the shortest path between A and B. For instance, as visualized in Figure 5.3, one would select three times the block that represents a straight road, and two times the block that resembles an intersection. The advantage of such a construction-kit based approach is the ability to use it for arbitrary road network layouts (as long as appropriate building blocks are existent), and arbitrary source and destination positions. However, in order to come up with valid estimates of the dissemination delay, it is essential to select blocks that model the characteristics of the road segment appropriately, e.g., with respect to its length, the number of lanes and traffic flow characteristics.

Basically, the proposed construction kit modeling approach employs the compositionality principle ([Fre84], [WHM12]), which is clarified in the Stanford Encyclopedia of Philosophy as:

> "The meaning of a complex expression is determined by its structure and the meanings of its constituents."[2]

within the context of dissemination delay modeling in inter-vehicle communication networks. The *meaning of its constituents* hereby corresponds to previously discussed building blocks, representing a certain delay characteristic, and the *structure* corresponds to the road network layout which determines existing information dissemination paths and has to be considered as is discussed later on in this section.

Decomposition approaches have in the past successfully been employed for the analysis of queuing networks, e.g., by Kuehn [Kue79] and Levy et al. [HL86]. In order to analyze the characteristics of a (complex) compound queuing network, it is broken down into easier to analyze subsystems and out of this overall characteristics are derived. Quite obviously, a decomposition approach is in particular suited if

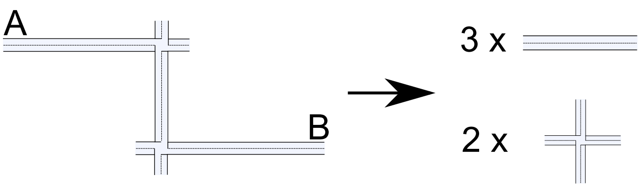

Figure 5.3: General construction kit concept, visualizing how a road network is divided in pre-defined blocks with known characteristics. Figure first published in [GMH12].

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[2] `http://plato.stanford.edu/entries/compositionality/` [last visited in December 2015]

there is no interdependency between the individual building blocks and less suited in case there is a strong interdependency. The common assumption of independence between inter-arrival and service times in queuing networks makes it intuitively more suited for a decomposition approach, compared to a vehicular network, where there is an obvious dependency of traffic flows on consecutive road segments. The dependency between two consecutive road segments can hereby vary a lot, depending on the actual traffic flows: It will probably be less severe in case multiple traffic flows merge, such as at a junction, compared to a continuation of a straight road segment where only several vehicles leave the highway. For this reason it appears apparent that the proposed modeling approach might have its limitations w.r.t. accurately predicting the dissemination delay for certain scenarios or conditions, in particular in case there are strong dependencies in traffic flows. In the evaluation section, this shortcoming will be picked up, discussed, and its impact will be demonstrated by means of different traffic flow characteristics.

Being able to estimate the dissemination delay over a given route is one part of the whole picture. When looking at a road network that consists of more than only a few road segments one has to consider all possible routes (or paths) based on which information could be disseminated from source to destination. For instance, if one wants to estimate the dissemination delay from position A to B within the road network depicted in Figure 5.4, one has to consider – amongst others – the paths labeled with I, II, and III. Each path will yield its own dissemination delay – in our example 59 seconds, 77 seconds, and 83 seconds respectively – and the one with the smallest delay determines the outcome of the estimation. Hence, one has to determine the shortest dissemination path between source and destination by using well established algorithms such as Dijkstra, Bellman-Ford or the Floyd-Warshall algorithm [BJG08].

A rather abstract view on our road network yields roads and intersections as coarse-grained blocks. This subdivision is also supported by most traffic simulators that built up their road network based upon these two building blocks. Coming from the same point of view, a road segment is generally described in a traffic simulator with its road length, its shape, the number of lanes for each direction, potential speed limits and rights of way – to name only a few. Describing an intersection additionally requires a specification of turning probabilities and/or route choices, as well as signal light schedules if traffic lights are existing.

According to Wischhof [Wis07] and Wu et al. [WFRH09], a dissemination process progresses (into the direction of the destination) either due to multi-hop forwarding or mobility. Wu et al. introduced the terms *forwarding phase* and *catch-up phase* to refer to these two possibilities. While forwarding is only possible within connected sub-networks, e.g., when there is a sufficient number of vehicles driving on the road as well as within each other's communication range such that multi-hop relaying is possible, a 'catch-up' is necessary whenever no forwarder within the communication range of the vehicle closest to the destination (termed *head vehicle* in the following) is available. In such a situation, progress is only achievable based on the mobility of the head vehicle itself. How often such a catch-up is required, and how long it takes to complete it depends on the vehicle distribution and the mobility of the head vehicle.

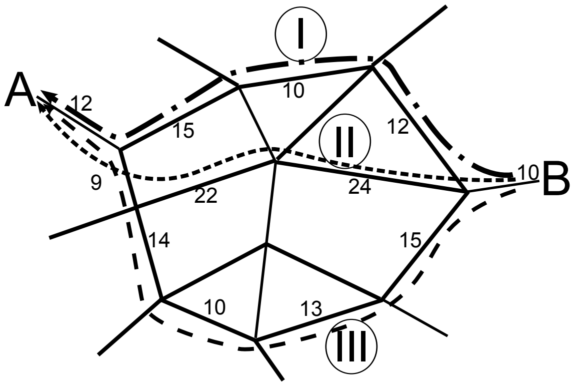


Figure 5.4: The road network is divided in predefined blocks with known characteristics. By means of graph-based algorithms the shortest path, in our case concerning the minimum delay, can be calculated between two arbitrary positions A and B in the road network. Figure first published in [GMH12].

The above elaborations show that the number of parameters that might have an influence on the dissemination delay is high. In order to keep the complexity manageable, we focused on only incorporating the factors that yield a significant impact on the dissemination delay. As a first step and as a preparation for the model building in the following sub-section we classify and discuss all parameters that will be considered in our analysis:

1. **Road network layout:**
   With respect to the road network layout, we consider the influence of the number of lanes in each direction and the length of a road. We also differentiate between a straight road and an intersection

2. **Mobility of the vehicles:**
   When it comes to mobility related parameters, we study the impact of the average vehicle velocity, the average inter-vehicle distance (IVD) – or inter-vehicle time (IVT) – and its distribution. Note that these two parameters are not completely independent as an increase of average velocities usually leads to greater inter-vehicle distances due to safety requirements. The IVD can directly be calculated as the arithmetic product of the IVT and velocity. We also evaluate whether different turning probabilities at an intersection affect the dissemination delay or not. While this should not be significant whenever there are enough vehicles on each road segment towards (or away from) the intersection, it will definitely be crucial in situations with a low vehicular density.

3. **Communication capabilities and radio propagation conditions:**
   With respect to communication capabilities and radio propagation conditions we evaluate the impact of different deterministic communication ranges and

line-of-sight (LOS) as well as non-line-of-sight (NLOS) conditions at intersections (e.g. due to buildings). Since the existence of NLOS conditions effectively reduces the number of potential forwarders at an intersection, it affects the minimum required traffic density at which a turning probability does not influence the dissemination delay significantly anymore.

4. **Data dissemination protocol:**
   As previously stated, we consider a beaconing-based dissemination scheme with piggybacking, which means that every vehicle is periodically sending out its locally collected (or sensed) information, and piggybacks received information to own packets. We therefore also study the impact of different beaconing intervals (or transmission rates), adaptive beaconing approaches such as the one proposed by Sommer et al. [STD10] and data aggregation schemes as the one proposed by Scheuermann et al. [SLRM09] or Dietzel et al. [DKHS11] are not considered.

5.4.2 Delay Characterization and Model Building

In this sub-section we first present the utilized scenarios and experiment design which we employed to characterize the speed of information dissemination. Then we present the methodology and parameter space that was used for our simulation-based study. Afterwards we highlight representative results for the straight road as well as the intersection block.

Scenario layout and experiment design

In order to identify and characterize the parameters that have to be considered for model building of the considered blocks we set up several scenarios. Besides a basic set of parameters that were varied within appropriate ranges for the considered layout (cf. Table 5.1 for the parameter ranges of the straight road block), we considered scenario specific properties as well. These are discussed next with respect to the basic scenario layout of a **straight road** and **intersection**.

Parameter	**Range**
Communication range	$[300, 600, 900]m$
Sending interval	$[5, 10]s$
Inter-vehicle time	$[10, 20, 30, 40]s$
IVT Distribution	$equidistant, exponential, Gaussian$
Average Velocity	$[15, 20, 33]m/s$

Table 5.1: Considered basic parameters and their ranges for an elementary straight road block.

Straight road scenarios: In order to assess the impact of mobility aspects for the straight road we considered a single lane and multiple lane layout. The general road layout of the multiple-lane scenario is depicted in Figure 5.5. There are two lanes

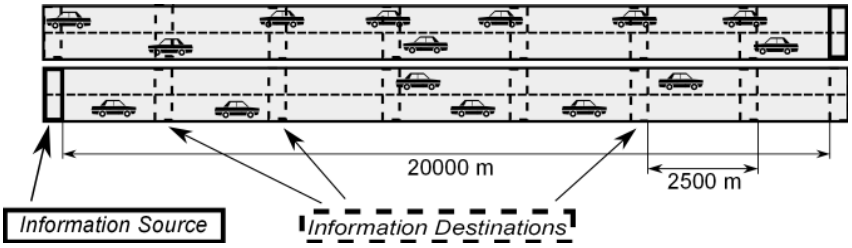


Figure 5.5: Basic multiple lane layout with two lanes per direction and a total length of 20 km. Figure first published in [GMH12].

going in each direction and the total length of the considered road is 20 km. The single lane layout is similar, with the exception that only one lane per direction exists and no overtaking is allowed. In total we set up the following straight road scenarios:

- **Homogeneous single-lane scenario:** In order to assess the impact of the before mentioned parameters without taking individual behavior into consideration we assumed (i) equidistantly distributed inter-vehicle distances on every lane and (ii) fixed and non varying velocities of all vehicles.
- **Exponentially distributed single-lane scenario:** In this scenario we assessed whether there is an impact on the dissemination delay if inter-vehicle distances are not equidistantly distributed. We therefore used exponentially distributed inter-vehicle times, as an empirical study [BK09] showed that they best fit realistic highway characteristics.
- **Varying velocities single-lane scenario:** In this scenario we dropped the assumption of fixed velocities. We assigned every vehicle a desired velocity out of a common velocity distribution. For instance, the desired velocity of an individual vehicle with an average velocity of 120 km/h ($\approx 33\, m/s$) was chosen from a distribution in the range between 85 km/h ($\approx 23\, m/s$) and 155 km/h ($\approx 43\, m/s$). Overtaking maneuvers, however, are prohibited in this scenario.
- **Multiple-lane scenario:** The multiple-lane scenario consists of two lanes per direction and overtaking maneuvers are allowed. With similar assumption as in the previous scenario (exponentially distributed IVTs and varying velocities) we were thus assessing whether the information delay benefits from overtaking maneuvers.

Intersection scenario: To get a better understanding of the parameters that have to be considered for an **intersection** model we set up the following scenarios for the general intersection layout that is depicted in Figure 5.6. We considered a four-way intersection and distinguished whether an information is disseminated straight over the intersection or whether it has to “turn” into a side road. Our focus in this set of scenarios is primarily to identify the impact of (i) varying turning probabilities (the probability that a vehicle turns left or right at an intersection) and (ii) the existence of non line-of-sight communication conditions on the dissemination delay.

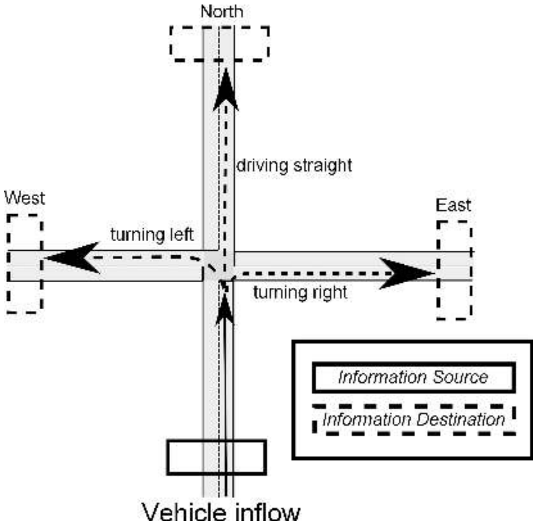


Figure 5.6: Basic four-way intersection layout. Figure first published in [GMH12].

- **One-inflow intersection:** In order to identify whether any influence of these two parameters is to be expected at all we set up a scenario with only one inflow (from the South). We varied the probability that a vehicle drives straight over the intersection from 20 % to 80 % in steps of 20 %. We assumed equal probabilities for turning right or left, which can hence be calculated according to $P(left) = \frac{1-P(straight)}{2}$, $P(right)$ accordingly. The length of the inflow and outflow road segments is 1 000 m each.
- **Four-inflows intersection:** In order to assess whether it is necessary to differentiate between an intersection and a straight road in a dense and rather homogeneous road network (with respect to the macroscopic traffic flow) we considered a scenario with constant inflows from all four directions. Since equal turning probabilities on all four inflows also result in equal outbound traffic we limited the adjustment of turning probabilities only to the inflow from the South. The vehicles coming from the other inflows are always passing straight the intersection. Furthermore, we assumed a non regulated intersection with traffic from the right having the right-of-way.

Methodology and simulation settings

Building a model that describes the dissemination delay for the considered blocks requires first and foremost a sufficiently large data basis. In order to cover the four categories mentioned earlier, we employed the traffic simulator VISSIM in version 5.40 to cover road layout and mobility aspects and the communication simulator NS-3 in version 3.12.1 [RH10] to take care of protocol and communication aspects. IEEE 802.11p settings with a center frequency of 5.9 GHz, a bandwidth of 10 MHz and a data rate of 6 Mbps were utilized. The wireless channel employs the RangePropagationLossModel of NS-3, which means that no propagation related communication errors occur up to the configured communication range, but interference could still prohibit otherwise successful receptions. Outside of the communication range reception attempts will never be successful. In order to model the impact of non line-of-sight conditions in intersection scenarios we use the VirtualSource11p propagation model proposed by Mangel et al. [MKH11].

Since we did not have to consider any feedback from the communication simulator to the traffic simulator, we first created mobility traces with VISSIM. These were then used by NS-3 to model the mobility of the vehicles. In every scenario layout we defined an *information source* and several *information destinations*, each with respect to a certain geographical area in the scenario. The information destinations are located at certain distances to the information source (e.g. 2 500 m, 5 000 m,…). In Figure 5.5 this concept is visualized by means of a multiple-lane scenario layout. In order to measure the delay between the information source and information destinations we implemented a **beaconing-based dissemination application** and conduct measurement experiments as follows:

- Every vehicle that passes the *information source* starts a new dissemination process (i.e. a new dissemination delay measurement experiment). That is, it creates a new entry in its own database, containing the own vehicle identifier, the current position and the current time.
- This entry is then broadcasted (together with received entries created by neighboring or remote vehicles) periodically in order to disseminate it towards the destination. In order to avoid capacity issues – we explicitly ignore data aggregation schemes in our study – we assume that the own entry and all piggybacked entries fit into one single packet.
- Upon reception of a packet, the own database is updated with the information contained in this packet, i.e., with the entries received. By doing so, every vehicle obtains a shared knowledge on "which vehicle has been starting its dissemination process at which point in time".
- Every time a vehicle passes one of the *information destinations* all its database entries are evaluated and the dissemination delay for each is calculated. Since one entry, i.e., the information corresponding to one dissemination process, may arrive several times at the *information destination*, only the first arrival is considered in our statistics.

Figure 5.7 exemplarily visualizes the variation of recorded dissemination delays at a distance of 20 km, once with equidistantly and once with exponentially distributed inter-vehicle distances. As can be seen, the dissemination delay of the process initiated by the first vehicle entering the road (simulated time = 0 s) is equal to the time it takes to drive to the destination, which equals 1 000 s (20 km with 20 m/s). This is expected, since there are no potential forwarders ahead of this vehicle who could speedup the dissemination process, i.e., the dissemination progresses only due to the mobility of the vehicle itself. With more vehicles entering the road (over time), the recorded delays decrease, since those vehicles can make use of preceding vehicles. Once the first vehicle arrives at the end of the 20 km long road (simulated time = 1 000 s), the initialization phase of our simulation is completed, and we start to consider recorded dissemination delays for our characterization and model building (*averaging phase*).

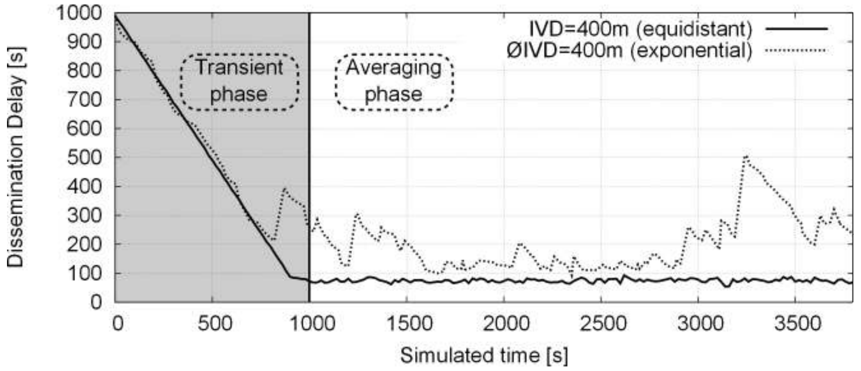


Figure 5.7: Variations of the measured dissemination delays over simulated time in one exemplary simulation run. Every vehicle entering the scenario starts a new measurement experiment and the experienced delay is evaluated after this information *traveled* a distance of 20 km. The scenario layout corresponds to a straight road with one lane per direction, a velocity of 20 m/s, a sending interval of 5 s, communication range of 600 meters, and IVDs distributed as stated within the figure.

Based on the collected measurements the mean dissemination delay is then calculated per building block and configuration and averaged over multiple simulation runs with different seeds for the random number generator. We hereby solely focused on calculating the mean dissemination delay, but it would similarly be possible to further consider occurring variances and generate a probability density function (PDF) out of the obtained results. In this case *adding* up the dissemination delay characteristics over multiple building blocks corresponds to a convolution and enables to make statements w.r.t. the relative likelihood of certain dissemination delay values to occur. Besides the calculation of the mean, mode, and median, the existence of a PDF further enables to calculate the probability that a certain upper bound delay cannot be fulfilled, which makes it of particular interest for dependability assessment.

The example illustrated in Figure 5.7 further demonstrates the difference between connected and only partially connected networks: while the recorded dissemination delay values exhibit only a very small variance in case of equidistantly distributed inter-vehicle distances, the variance is rather large in case of exponentially distributed IVDs (stated IVDs are mean values). This is attributed to the fact that no catch-up phases are needed in the first case (600 m communication range vs. equidistant 400 m IVD) and the observable delay variations are hence only due to differences in the communication protocol stack behavior, in contrast to the second case, where IVDs can occur which cannot be bridged by means of communication. It can also be seen that the recorded delay values correlate with time, since two subsequent vehicles experience very similar traffic conditions. This characteristic is, for instance, visible at the simulated time of approx. 3 200*s* for exponentially distributed IVDs: A rather extensive catch-up phase results in a significant increase of the measured dissemination delay, which is due to an only partially connected network and the oncoming traffic not being able to bridge this gap for a long time. Subsequent vehicles hereby experience rather similar conditions, which only slowly improve over time.

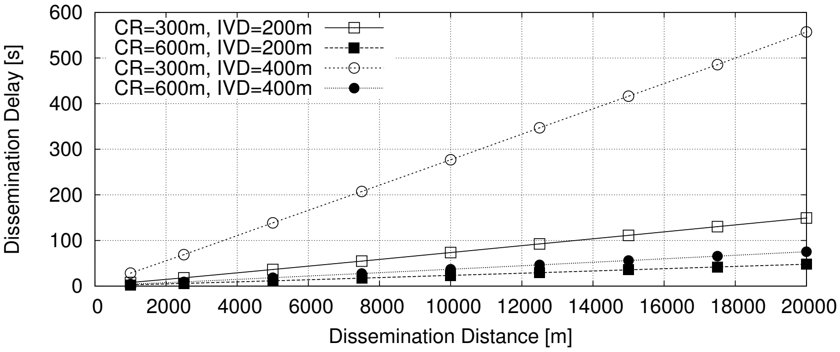


Figure 5.8: Impact of varying communication ranges and inter-vehicle distances in the *homogeneous single-lane scenario* on the dissemination delay. There is one lane per direction, opposite traffic is available and IVDs are stated per lane. Vehicle velocity is a constant 20 m/s, sending interval 5 s and equidistantly distributed vehicles are assumed. Figure first published in [GMH12].

Characterization and selected results

Straight road scenario: When considering a straight road scenario the relationship between the inter-vehicle distance (IVD) and the communication range is essential. In the homogeneous scenario with equidistantly distributed vehicles and non varying velocities i) a communication between any two vehicles on the same road can either take place over the whole simulation time or not all and ii) the network is fully connected if the IVD is smaller than the communication range. The impact of the relationship between the IVD and communication range is depicted in Figure 5.8. A higher communication range extends the progress that is achieved per hop, thus increases the number of potential forwarders and consequently lowers the dissemination delay. The maximum expected dissemination delay for a distance of 20 000 m with a velocity of 20 m/s is 1 000 seconds. Even with a communication range of only 300 meters and an inter-vehicle distance of 400 meters per lane, however, the dissemination delay is below this maximum value by making use of the opposite traffic. A further observation of Figure 5.8 is the linear increase of the dissemination delay. This is of particular interest, since it enables to define straight road blocks with a fixed length that can then be scaled to the desired road length.

Figure 5.9 illustrates the impact of exponentially instead of equidistantly distributed IVDs. There is a clear increase of the dissemination delay for IVDs of 200 and 400 meters. This increase is attributed to the fact that due to exponentially distributed IVDs several clusters might form. Note that even though the dissemination delay on a per vehicle basis noticeably fluctuates (as seen in Figure 5.7) the average dissemination delay linearly increases. With fixed and constant velocities an information between two clusters on the same lane can only be propagated by the opposite traffic with a negative impact on the dissemination delay. With an equidistant IVD of 800 meters and the considered communication range of 300 meters there is no possibility to exchange information by means of communication with any vehicle that

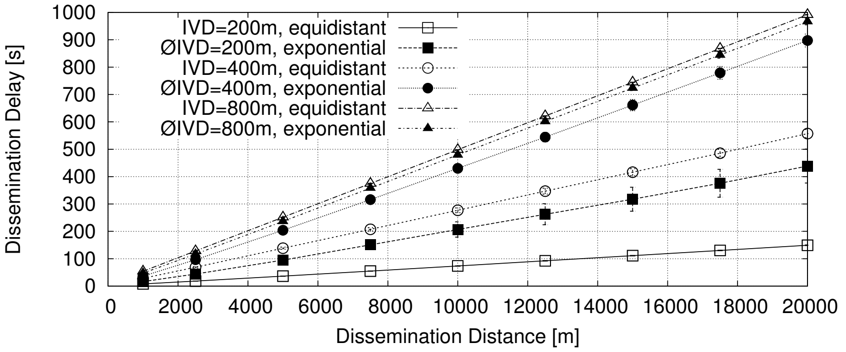


Figure 5.9: Impact of exponentially instead of equidistantly distributed inter-vehicle distances on the dissemination delay in the single-lane (one per direction) scenario with opposite traffic. Vehicle velocity is a constant 20 m/s, sending interval 5 s and 300 meters communication range. Figure first published in [GMH12].

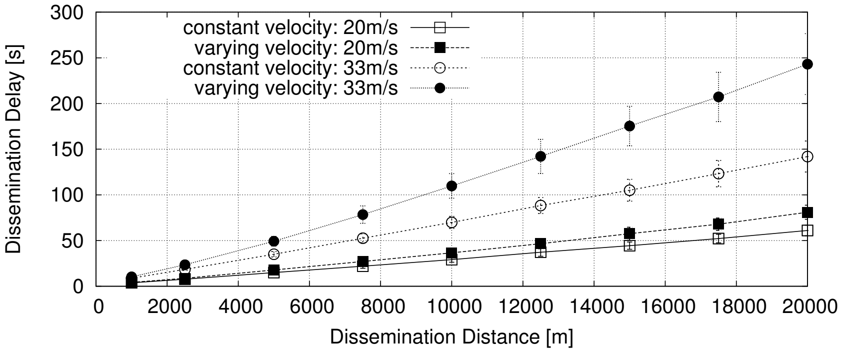


Figure 5.10: Impact of varying velocities on the dissemination delay on a single-lane scenario with opposite traffic. Sending interval is 5 s, inter-vehicle times are assumed to be exponentially distributed with a mean of 10 seconds per lane, communication range: 600 meters. Figure first published in [GMH12].

is driving ahead on the same lane. Consequently, the dissemination delay results in the maximum of 1 000 seconds. With exponentially distributed IVDs, but otherwise unchanged conditions, small vehicle clusters might form and as a consequence the average dissemination delay decreases.

In order to evaluate whether the dissemination delay is sensitive to varying velocities we set up two scenarios in which equal inter-vehicle times but different and varying velocities are used. Figure 5.10 presents the results for the single-lane scenario (one per direction) and no possibility to overtake. As can be seen, the dissemination delay increases with the average velocity configured and the level of variation. This effect is attributed to the fact that vehicle clusters are formed more often in these cases, either because of the chance that slower vehicles (which cannot be overtaken) facilitate clustering, or because of larger (average) IVDs. Hence, there are less receptions and potential forwarders of a packet transmission. In a dissemination process that is primarily influenced by communication aspects (fully or close to fully connected networks) this consequently leads to an increase of the dissemination delay as seen in Figure 5.10.

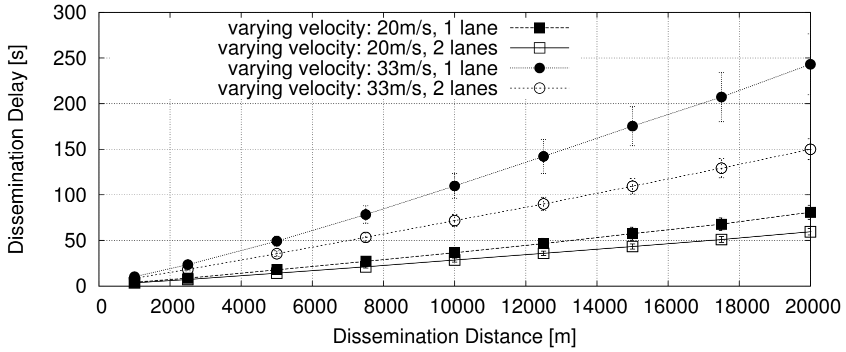


Figure 5.11: Impact of varying velocities on the dissemination delay on a two-lane scenario with opposite traffic (Highway). Sending interval is 5 s, inter-vehicle times are assumed to be exponentially distributed with a mean of 20 s per lane (resulting in the same IVT per direction as in Figure 5.10), communication range: 600 meters. Figure first published in [GMH12].

Figure 5.11 evaluates whether the existence of a second lane and thus the opportunity to overtake supports the dissemination delay. We adjusted the inter-vehicle time per lane to have a similar vehicle density per direction as in the previous scenario. It is clearly visible that the dissemination delay is reduced if the possibility to overtake exists. This is reasoned by the presence of faster vehicles which are able to *carry forward* information by being able to pass slower vehicles and that are also able to *bridge* between two clusters.

One-inflow intersection: In order to get a first understanding of the impact of previously mentioned intersection specific parameters (turning probabilities and LOS/NLOS communication conditions) we considered the layout depicted in Figure 5.6. There is only one inflow and every vehicle independently decides whether it is going to turn left/right or drives straight across the intersection. The length of every street segment is 1 000 m.

Table 5.2 exemplarily indicates – for an inter-vehicle time of 10 seconds at the inflow and varying turning probabilities as well as IVT distributions – the resulting dissemination delays for a dissemination process from the *Information Source* to the *North* (cf. Figure 5.6). The distance between these two locations is 2 000 m.

The first column (LOS) corresponds to the dissemination delay for the LOS communication model. Two observations can be made: First, the dissemination delay decreases as more vehicles are driving straight across the intersection. Second, the dissemination delay for exponentially distributed IVTs is higher than for the equidistant distribution. Both observations correspond to the results seen for the straight roads. The turning probability directly influences the IVT and vehicle density on the subsequent roads and consequently the speed of information dissemination. However, it should be noted, that if an equidistant IVT distribution is assumed at the inflow this doesn't hold for subsequent roads, due to the turning behavior randomness. In general, this leads to higher dissemination delays as gaps between vehicles might be created that cannot be *bridged* by means of communication.

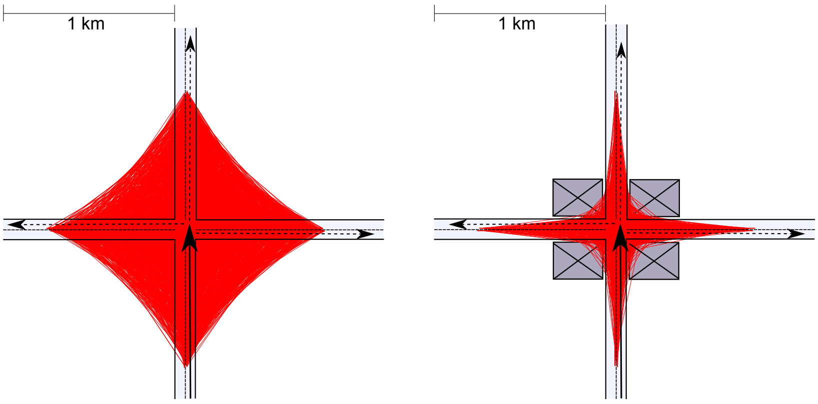
Parameters		Delay[s] (Variance)		
P(straight)	**IVT dist**	**LOS**	**NLOS**	**w/o transverse**
20 %	equidistant	55.4 (4.8)	61.3 (4.4)	63.2 (5.3)
40 %	equidistant	24.2 (2.2)	28.0 (2.4)	28.5 (2.5)
60 %	equidistant	12.3 (1.0)	13.7 (1.3)	13.8 (1.3)
80 %	equidistant	8.2 (0.4)	8.6 (0.5)	8.6 (0.5)
20 %	exponential	71.5 (8.8)	79.5 (10.2)	76.1 (11.8)
40 %	exponential	43.3 (4.8)	50.4 (8.1)	47.2 (7.1)
60 %	exponential	29.8 (3.8)	34.9 (5.7)	33.3 (4.6)
80 %	exponential	26.9 (3.9)	29.7 (6.3)	29.4 (5.6)

Table 5.2: Dissemination delay from *South* to *North* (cf. Figure 5.6) for the "one-inflow intersection" with varying turning probabilities. Average inter-vehicle time is fixed to 10 s with equidistant and exponentially distributed IVTs and the velocity is fixed to 15 m/s for every vehicle. Results for LOS communication conditions, NLOS conditions, as well as without the consideration of vehicles on transverse roads (w/o transverse) are presented.

In the second column (NLOS) we present the results for the NLOS communication model. The corresponding connectivity plot in Figure 5.12b visualizes that communication *around the corner* is only possible in close vicinity to the intersection center. Hence, there are in general less potential forwarding vehicles on the transverse roads and the dissemination delay consequently increases as can be seen in the second column. To affirm this observation we additionally considered the case that vehicles on the transverse roads do not take part in the information dissemination process at all. These results are shown in the third column and are, as expected, similar to the NLOS case.

The presented results indicate the necessity to consider intersections as individual blocks, due to i) the influence of transverse roads that are in general present at intersections and ii) a potential change of the distribution of inter-vehicle times right after an intersection. It has been shown that the presence of further vehicles, even on transverse roads, support the information dissemination process while a change in the IVT distribution might slow it down. We compared the dissemination delay of the considered intersection scenario with a total road length of 2 km to the delay of two one kilometer straight road blocks with corresponding IVT and velocity properties. A delay difference was primarily noticeable for equidistantly distributed IVTs, due to the given reasons, and for exponentially distributed IVTs there were some minor, but still noticeable variations. It should, however, be noted that traffic conditions might exist which allow to neglect the influence of intersections. Further, depending on the actual use case and the ratio of total road length to number of intersections, scenarios are conceivable where the impact of intersections might be negligible in the end.

Figure 5.13 distinguishes between the dissemination delay on the main (straight) road and on the side roads. It is clearly visible that there is an opposed impact on both dissemination paths, resulting from the *allocation* of vehicles on subsequent roads, according to the turning probability.



(a) LOS communication model (b) NLOS communication model

Figure 5.12: Connectivity plots, visualizing the communication conditions in the four-way intersection scenario. One line is drawn per successful information exchange between two vehicles. Figure first published in [GMH12].

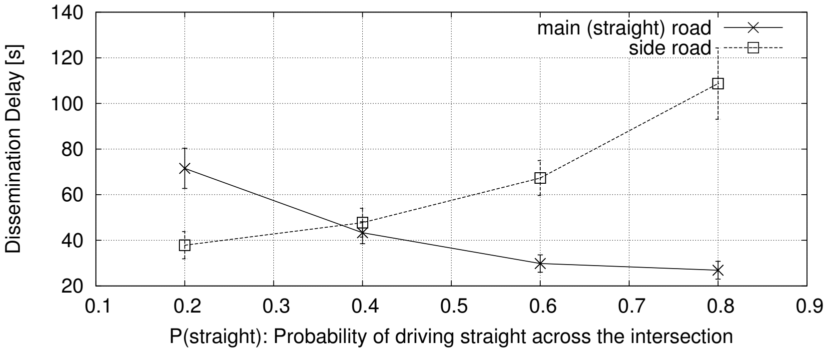


Figure 5.13: Dissemination delay separated by the direction of dissemination in the main (straight) road or side road. Only one inflow exists, IVTs are equidistantly distributed with 10 s and the vehicle velocity is 15 m/s. Figure first published in [GMH12].

Four-inflows intersection: In order to evaluate the influence of varying turning probabilities in more detail, we set up a scenario with inflows from all directions. The turning probability was, as discussed earlier, only varied for one inflow. In Figure 5.14 we plot the information delay with respect to the dissemination direction: to the North, South, East or West of the scenario. When looking at the scenario layout again, there is always at least a constant flow towards the South, East and West. The only vehicles driving towards the North are the vehicles coming from the adjustable inflow and driving straight over the intersection. There is no clear dependency visible between the turning probability and the resulting dissemination delay if a constant vehicle flow is present (towards the South, East and West) and even though the traffic flow changes here as well, no further benefit of more vehicles can be observed. Contrary, the dissemination delay towards the North is directly influenced by the percentage of vehicles driving in this direction as no other traffic flow exists.

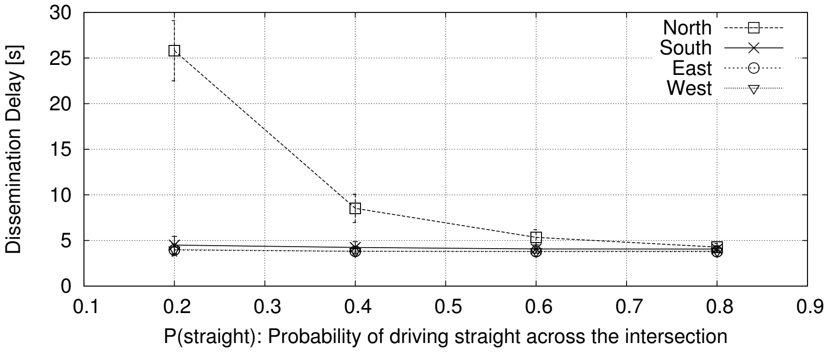


Figure 5.14: Dissemination delay separated by the direction of dissemination towards North, South, East and West. Four inflows exist, but only the South inflow is influenced by the turning probability. IVTs are equidistantly distributed with 10 seconds and vehicle velocity is 15 m/s. Figure first published in [GMH12].

5.5 Applicability and Evaluation of the Modeling Approach

In order to evaluate the general applicability of the proposed construction kit modeling approach as well as to get an understanding in which situations which deviations compared to a packet-based simulation approach have to be expected we performed an evaluation in a subsequent step. The overall employed evaluation methodology is hereby visualized in Figure 5.15.

In a first step we utilized previously obtained dissemination delay results of our simulation study and performed model building for *straight road* and *intersection* blocks (whereby we calculated the average delay over multiple simulation runs with 10 different seeds for the random number generator (RNG) per parameter configuration). The models are hereby realized as simple lookup tables with linear interpolation between given points and incorporates previously discussed parameters related to road layout, mobility of vehicles, as well as communication and propagation conditions. Within the context of this chapter, this modeling approach allowed us to focus on the fundamental question of whether a decomposition of the network is possible at all, for future use in simulation studies a different model realizations, e.g., by means of curve fitting, might be better suited.

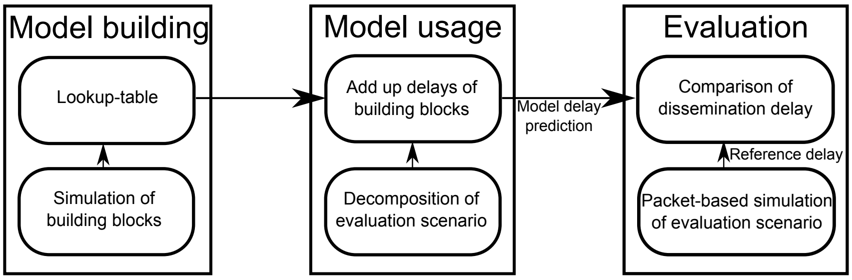


Figure 5.15: Employed methodology to evaluate the applicability of the proposed *construction kit* modeling approach.

Our evaluation scenario is similar to the one shown in Figure 5.3 which consists of three straight road blocks, varying in length, and two intersections, resulting in a total length of 11 km that the information had to travel from information source to destination. For our dissemination delay prediction we decomposed the overall scenario into its building blocks and added up the dissemination delays per block, which we determined based on the created lookup table and which considers, e.g., the traffic density or average velocity.

We limited the evaluation scenario to a size which can still be simulated by means of commonly employed packet-based simulation models *in one piece* and employed it as a reference. Overall there were up to 2 500 vehicles traversing the reference scenario over a simulation duration of 4 200 seconds and in order to ensure statistical significance, we simulated it 10 times with a different seed for the RNG. In order to get a better understanding on when the proposed modeling approach is applicable, we varied the IVTs, their distribution and assumed various traffic conditions, with respect to the number of inflows or turning behavior. As traffic conditions we hereby assumed i) only traffic going in one direction, ii) traffic going in both directions, and iii) heterogeneous vehicular traffic with vehicles potentially entering or leaving the scenario at each intersection along the way. While for assessing the applicability of the decomposition approach in realistic traffic scenarios the third option is obviously the most relevant one, the other options allow us identify potential restrictions. In particular, these scenarios represent conditions in which there is a high dependency between consecutive road segments and hence demonstrates whether the decomposition approach is even applicable in these situations and which deviations have to be expected.

The achieved results are depicted in Table 5.3. The first column per scenario lists the measured average delay as calculated by time-consuming packet-based simulation and in the second column the difference in dissemination delay compared to the proposed construction kit modeling approach is presented in relative as well as absolute values. Negative values hereby correspond to the construction kit model underestimating the dissemination delay. The largest relative deviations are highlighted.

	Scenario / Traffic flow:					
IVT	Unidirectional		Bidirectional		Heterogeneous	
distribution	Delay	Diff.	Delay	Diff.	Delay	Diff.
10 s equi.	31.8 s	-1 % (-0.2 s)	19.1 s	7 % (1.4 s)	21.1 s	-4 % (-0.9 s)
20 s equi.	50.3 s	7 % (3.7 s)	35.2 s	5 % (1.7 s)	49.1 s	-27 % (-13 s)
10 s exp.	237.6 s	-31 % (-72.5 s)	26.2 s	15 % (3.9 s)	25 s	15 % (3.8 s)
20 s exp.	431.6 s	-18 % (-76.7 s)	109.7 s	-3 % (-3.3 s)	98.1 s	-1 % (-0.7 s)

Table 5.3: Dissemination delay in the reference scenario with an average velocity of 20 m/s, a communication range of 600 meters, and a sending interval of 5 seconds. Inter-vehicle times are considered to be either equidistantly or exponentially distributed with a mean of 10 or 20 seconds. The difference to the dissemination delay as calculated by the construction kit modeling approach is presented in percentage as well as in absolute values and the most severe outliers are highlighted.

It can be seen that with equidistantly distributed IVTs the decomposition approach works without significant flaws in almost every considered scenario. As can be seen by means of the *heterogeneous* scenario, the presence of intersections, however, can result in more severe deviations which is due to a change of IVT distribution on successive road segments (leading away from the intersections) since vehicles might have to stop for giving the right of way at intersections. Since not all potentially resulting distributions have been considered in the model building step, the existence of intersections therefore lead to deviations which might not be tolerable anymore. Its impact is particularly visible for higher IVTs (cf. 20 s vs. 10 s) since in these cases there is a higher probability of resulting inter-vehicle distances on roads leading away from an intersection which cannot be bridged by means of communication. Yet, this is no fundamental issue and can be solved by developing blocks that represent these potential distributions.

With exponentially distributed IVTs the largest differences exist in the *unidirectional* scenarios in which only one homogeneous and partitioned traffic flow in one direction exists. In these scenarios, that do not exhibit changes over time, there is an obvious dependency between consecutive road segments, since formed clusters last over successive building blocks. Due to this fact, it is apparent that the decomposition approach, which treats successive road segments independently from each other, is not able to appropriately represent these situations and as a consequence, the dissemination delays are underestimated. The presence of multiple vehicle flows, non constant velocities or overtaking maneuvers, that are present in heterogeneous and realistic scenarios, however, drastically reduces this effect. This effect is visible in the *bidirectional* and *heterogeneous* scenarios, where the delay differences are still perceptible, but less significant than in the unidirectional scenario. In absolute terms the difference is less than 4 seconds and can similarly be reasoned on the one hand due to network effects and on the other hand due to resulting conditions on the roads which have not been considered in model building.

With respect to the intended use case of the proposed model, which is to depict expected average information dissemination characteristics that have to be expected in large-scale scenarios and which then could be employed, e.g., for performing impact assessment of efficiency related inter-vehicle communication applications, the achieved accuracy appears to be sufficient. It is quite obvious and has been shown that its predictions might not be tolerable for safety related considerations where the actual focus is to determine whether the communication system is suited for giving advices in time and this on a time scale in the order of a few seconds or even split seconds. However, the scope of these studies can generally be limited to a few hundred vehicles and a spatial environment of only some kilometers which can be addressed by current packet-based simulation models. Compared to commonly employed models, the proposed approach, however, enables to extend the scope of inter-vehicle communication related simulation studies beyond what is currently feasible and is hence contributing in finding answers to the question of "how inter-vehicle communication is changing the way of how we drive and travel".

5.6 Summary and Future Work

In this chapter we have addressed the raised research question of whether it is possible to macroscopically model information dissemination in inter-vehicle communication networks. Our motivation for doing so was the observation that the current process of modeling the information dissemination in inter-vehicle communication networks comprises the usage of highly detailed (packet-based) communication models which prevents assessing its large-scale impact – which traffic engineers are interested in and what is required by decision makers – due to scalability issues. We hence proposed and discussed the concept of a framework on how an information-centric modeling approach can be realized for inter-vehicle communication networks. The basic idea of the concept is to make use of the global knowledge that the traffic simulator already possesses on traffic conditions instead of expensively building up this information at every vehicle in the road network by means of millions of exchanged packets. The concept proposes a three-stage process which consists of i) extraction, ii) storage, and iii) filtering of traffic snapshots to derive local views of vehicles in the road network. We demonstrated that the two first steps pose no further challenge, w.r.t., computation and storage requirements, but pointed out that the filtering-step is crucial for an accurate modeling and has to incorporate important characteristics of information dissemination, such as the dissemination delay or granularity of disseminated information.

Since we identified that there is yet a comprehensive understanding missing how the combined influence of road network layout, mobility as well as communication aspects influence the characteristics of information dissemination, which is a prerequisite for building accurate filter functions, we subsequently focused on characterizing its impact on the information dissemination delay. We performed an extensive simulation study which characterized the impact of a multitude of parameters, such as the inter-vehicle distribution, communication range, average velocities, or road layout on the dissemination delay. Based on these insights we were then able to propose an information-centric modeling approach to model the dissemination delay in arbitrary road networks. The modeling approach is based on a *divide and conquer* principle in which the entire road network is decomposed into elementary building blocks with known dissemination delay characteristics. We contributed by providing two of these elementary blocks: a straight road of arbitrary length for highway, rural and city scenarios, as well as an intersection with characteristics which originated from the conducted extensive simulation study. In our evaluation we have pointed out that this decomposition approach generally works and is able to appropriately model the dissemination delay in most conditions, but we also identified limitations under which conditions and for which considerations the proposed approach might not be appropriate.

With respect to the posed research question we can hence conclude that the proposed modeling approach is able to macroscopically model the information dissemination delay in inter-vehicle communication networks, enabling future simulation studies to assess the impact of vehicular communication on road traffic on a larger scale than possible before.

Future work

Future work is conceivable in multiple dimensions – from making use of the achieved insights to assess whether the information dissemination characteristics of the currently envisioned vehicular communication system is sufficient for envisioned vehicular applications, employing the developed modeling approaches to broaden the scope of future simulations studies, or refining and extending the proposed model to incorporate additional aspects. An obvious subsequent step is the creation of additional building blocks, refining scenario layout specifics, or including additional traffic flow characteristics. Even though these extensions might be necessary before being able to employ the modeling approach in highly heterogeneous networks, no significant new insights have to be expected. Since we identified the importance of mobility aspects on the speed of information dissemination, it would, however, be worth to integrate realistic large-scale mobility patterns in the modeling phase, which could, for instance, be collected during large-scale field operational tests. Another direction of future work is to employ the performed delay characterization as input for inter-vehicle routing algorithms, i.e., to specify the weight of edges according to present traffic and communication conditions, in order to reduce the dissemination delay up to a certain recipient or geographical area or save transmission capacities by only selecting the most promising dissemination path. While within this chapter, we primarily focused on characterizing the average delay in given situations we gained as well insight in the variance that it is subjected to. As a future work, these insights could first be extended and then be employed as input for finding optimal routes in Stochastic On-Time Arrival (SOTA) problems [NW09]. Contrary to most routing algorithms, which usually solely try to minimize, e.g., the travel times, the general idea behind SOTA algorithms is to maximize the reliability that information is available at some destination within a given time frame. In order to increase the dependability of the availability of information this approach therefore not only relies on accurate average predictions, but also on the characterization of unreliability, e.g., in the form of a probability distribution function of the to be expected dissemination delay.

6
Conclusions

Simulation-based assessment has accompanied research and development of inter-vehicle communication over a long period of time. It was an essential part from the early years until nowadays with a steady change in focus – from assessing the general feasibility of vehicular communication to performing impact assessment. Simulation-based assessment has therefore contributed a major part in the development of nowadays envisioned protocols and has also led to the current understanding that we have on vehicular communications' capabilities. A key aspect of inter-vehicle communication and a central issue of simulation studies which have been performed over all these years is *dependability*. It determines the suitability of inter-vehicle communication to improve our road transportation system on multiple levels. Safety related functions, for instance, rely on a reliable exchange of messages in order to be able to advice the driver in time, while several efficiency related functions try to achieve reliability in travel times, e.g., by advising the driver to take an alternative route in case the regular route is congested. While dependability can hence be identified as a central issue, the employed simulation tools and as a result the utilized models significantly vary, depending on the focus of the study and research community. Throughout the years a multitude of different models have been proposed, with some of them realizing the same aspect, but on different abstraction levels, e.g., radio propagation conditions on a signal level and packet level. While in this case it is not clear whether the different modeling approaches make up a coherent picture and hence comply with the requirement of multiscale modeling, there are other areas where modeling approaches are still missing for achieving a comprehensive multiscale modeling of inter-vehicle communication.

Within this thesis we have addressed the following three issues in the context of multiscale modeling and with the objective to further advance towards a comprehensive understanding of the capabilities and dependability of inter-vehicle communication:

1. Fine grained microscopic modeling of urban **radio propagation** conditions and identification in which situations commonly employed propagation models might not yield appropriate results.
2. Assessment of the dependability of two fundamentally different decentralized **medium access control** schemes – the random access IEEE 802.11p protocol in comparison to the reservation-based STDMA protocol – and identification in which situations the largest differences have to be expected.
3. Design of an information-centric modeling concept and development of a macroscopic model which allows to determine the **information dissemination** delay in inter-vehicle communication networks.

Within these three domains, which cover central aspects of today's inter-vehicle communication dependability assessment and span from signal up to information level, we can conclude that multiscale consistency between different modeling approaches is either existent, e.g., from signal to packet-level propagation modeling, or can be realized, e.g., from packet to information-level dissemination modeling. We further showed that even substantial differences, such as the deployment of a fundamentally different decentralized coordination scheme does not necessarily invalidate the consistency across multiple model hierarchies or requires a distinct consideration in the spirit of a macroscopic inter-vehicle communication model. The contributions of this thesis as well as insights, in particular with respect to the second motivational question of identifying and characterizing the conditions which significantly influence the dependability within the three considered domains, are individually presented and discussed in the following. Directions for future work are only briefly sketched in the following, since it has already been extensively discussed within the respective chapters.

Radio propagation: We employed a ray tracing approach to microscopically model urban radio propagation conditions in order to assess the impact of radio obstruction variations. On the one hand and from a dependability assessment point of view this revealed situations which are most crucial for inter-vehicle urban communication and on the other hand, w.r.t. assessing differences in urban radio propagation modeling, this enabled us to evaluate which particular situations can be appropriately modeled by (which) commonly employed urban radio propagation model. Our assessment revealed that while under line-of-sight conditions the degree and character of radio obstacles noticeably influence the path loss and that there is a clear trend observable between different obstruction levels, its distinguishability diminishes under non line-of-sight condition. Under line-of-sight conditions we generally identified three possible variations, i) a blank scenario layout where multipath propagation effects are clearly visible, ii) a densely populated scenario where a multitude of obstacles, e.g., parking vehicles, constructively contribute to radio conditions and iii) obstructed line-of-sight conditions, where blocking of the strong line-of-sight path results in rather severe radio conditions. A comparison to commonly employed models then revealed that while obviously small scale differences exist, the general trend of all three variations can be appropriately matched by respective simplified path loss models. In order to quantify the occurring differences due to different modeling approaches on metrics which are in the focus of network oriented research, we performed an assessment by means of the packet reception probability, packet inter-arrival time, the first packet reception distance and regular packet distance, and found even diminishing impacts, compared to a comparison on the path loss level.

Consequently, our analysis justified the abstraction level of currently employed urban radio propagation models for most network oriented research, but at the same time demonstrated that these models might not be appropriate for dependability assessment of safety related functions where accuracies of a few meters can be decisive.

Future studies can benefit from the achieved insights on the one hand by being able to make sound decisions on the applicability of their employed urban radio propagation model to represent intended situations. On the other hand our results indicate which outliers protocols and applications have to expect in an ordinary urban inner-city scenario and hence reveal a minimum requirement of robustness which has to be ensured.

Decentralized channel coordination: We assessed and compared the two most prominent, but fundamentally different decentralized coordination schemes for inter-vehicle communication networks. Since contrary to CSMA/CA, a profound understanding of the dependability of STDMA to schedule periodic messages in an inter-vehicle communication network is missing, we first identified its fundamental characteristics, i.e., we identified the situations in which successful coordination amongst neighboring stations cannot be achieved. We pointed out that even under perfect communication conditions either bad luck at startup or local slot congestion can result in stations not being coordinated amongst each other in a non-saturated network. In order to quantify these situations to occur, but also to incorporate effects, such as channel fading or mobility, which are inevitable in a vehicular environment we contributed a model of the STDMA protocol to the well known network simulator NS-3. By means of an extensive simulation study we first identified how STDMA's protocol parametrization influences its capability to successfully coordinate the channel access in a vehicular environment and we propose a parametrization which yields to be suited for a vehicular deployment. Based on this protocol parametrization we identified that STDMA is well capable of handling rather high channel load situations but is more prone to individual incoordinated stations, compared to CSMA. Hence, we subsequently focused on evaluating to which extent the coordination performance of STDMA is influenced in a vehicular environment compared to CSMA and identified the following fundamental differences:

1. Contrary to CSMA, hidden nodes are able to introduce new slot allocation collisions with otherwise coordinated nodes in an STDMA network, since their interference can result in crucial reservation information being non decodable. Due to the synchronized approach of STDMA, however, there are overall less incoordinated hidden nodes which can interfere ongoing transmissions, compared to CSMA.

2. The existence of severe fading conditions are in general less detrimental for STDMA than for CSMA. With STDMA, either previously made slot allocations are simply adhered to or in case a new slot allocation is required, previously received information can be incorporated. On the contrary, CSMA primarily relies on current conditions to decide on which node is allowed to transmit next and is hence more prone to temporary fluctuations.
3. While the reservation-based approach of STDMA is hence beneficial to cope with temporary fluctuations, such as channel fading, it has a detrimental effect whenever the vicinity of a station changes, such as due to mobility. This can be reasoned by vehicles with a different view on slot allocations encountering each other, but having to adhere to previously made reservations before being able to resolve existing collisions, which is not necessarily successful right away.

Whereas the fundamental different coordination approaches of STDMA and CSMA likewise result in different strengths and weaknesses in dealing with particular conditions, as our evaluation of the coordination ability has pointed out, the differences diminish on *higher layers*. Our assessment by means of the packet delivery ratio and packet inter-arrival time indicates that applications, building on top of exchanged periodic messages, do not experience a significant different communication behavior and dependability. These results hence allow to abstract from a particular coordination scheme in the spirit of macroscopic inter-vehicle communication modeling. For future work it would be worth considering whether centralized TDMA approaches, which might become an option for platooning, change the overall picture on the dependability of periodic message exchange in inter-vehicle communication networks. With respect to STDMA, there is promising future work w.r.t. evaluating its suitability to transmit event-driven messages as well as to identify the optimal channel load in given situations and ways on how to adhere to it, similarly to current power and rate control mechanisms.

Information dissemination: Since there is a high demand to assess the benefit of inter-vehicle communication on our road transportation system, but currently existing communication models preventing desired large-scale assessments, we discussed and presented a generic concept which does not rely on representing what is actually going on in reality, i.e., the exchange of millions of packets between participating nodes, but instead makes use of the global information which is available at the traffic simulator. We demonstrated the technical feasibility of this concept, but identified that the data basis was missing which describes how the global knowledge has to be altered to accurately represent the characteristic of information dissemination in inter-vehicle communication networks. In order to address this shortcoming we subsequently performed an extensive simulation-based study to characterize the impact of road network layout, mobility, as well as communication aspects on the speed of information dissemination. On the one hand the results of this study contributed in a better understanding of which factors influence the speed of information dissemination in which way and on the other hand we were able to utilize the obtained results for model building of an information-centric modeling approach. Our proposed model is hereby based on a *divide-and-conquer* principle which divides the entire road network into building blocks with known delay characteristic. The approach is hence applicable to arbitrary road networks and enables to model the dissemination delay in a light-weight fashion. Contrary to commonly employed simulation approaches, which focus on assessing the impact of individual packet receptions on communication protocols or applications, the proposed approach is focused towards assessing the impact of vehicular communication on road traffic. The conducted evaluation demonstrated a reasonable consistency of the proposed modeling approach compared to packet-based simulation for simulation studies where the focus is to depict average information dissemination characteristics and not individual outliers. The proposed approach hence enables future work in the context of assessing the large-scale impact of inter-vehicle communication on our road transportation system. In future work the proposed information-centric modeling approach can be extended by not only considering the delay characteristics but by also incorporating how information is altered, e.g., aggregated, as it is disseminated in an inter-vehicle network. The proposed methodology can hereby similarly be applied, protocol specifics of the employed multi-hop dissemination protocol, however, have to be considered more in detail in this case.

The core contributions of this thesis can be summarized as:

1. We **justified the abstraction level of currently employed urban radio propagation models for network oriented research** and enable future research to make **sound decisions on the applicability of existing modeling approaches** for certain use cases and to depict particular radio situations.
2. We **quantified the differences** which have to be expected for inter-vehicle communication applications when employing different decentralized coordination schemes – **random access vs. reservation-based** – on the basis of two prominent representatives: IEEE 802.11p CSMA/CA and STDMA. While in detail different **strengths and weaknesses have been identified**, the overall results **justify to abstract from a particular decentralized coordination scheme** realization with regard to a macroscopic modeling of inter-vehicle communication.
3. We proposed an **information-centric modeling approach** which enables to predict the information dissemination delay in an inter-vehicle communication network without the necessity to expensively model the exchange of millions of packets, as is done nowadays. We hence demonstrated the general feasibility of a **macroscopic modeling approach for the simulation of the dissemination delay in inter-vehicle communication networks**.

In a broader context, inter-vehicle communication networks are a building block of future ubiquitous informatics systems which will accompany us in every aspect of our life. Since a requirement of ubiquitous systems is to be able to constantly communicate with each and everyone, the wireless system has to be sufficiently robust and be able to cope with existing uncertainties. Within this thesis we hence not only contribute by quantifying uncertainties which have to be expected in one aspect of future ubiquitous informatics systems, but also by providing a solid foundation which can be picked up for reliability engineering of future mobility systems.

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