Felix Schmidt-Eisenlohr

Interference in Vehicle-to-Vehicle Communication Networks

Analysis, Modeling, Simulation and Assessment

KIT Scientific Publishing

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Zusammenfassung

Fahrzeug-zu-X (engl. Vehicle-to-X (V2X)) Kommunikation, die direkte Kommunikation zwischen Fahrzeugen und/oder die Kommunikation zwischen Fahrzeugen und stationären Infrastrukturpunkten, beschreibt die eine in Entwicklung befindliche Technologie, die für verbesserte kooperative Sicherheitssysteme, verbesserte Verkehrseffizienz sowie die Unterstützung von Infotainment-Anwendungen zum Einsatz gebracht werden soll. Um kooperative Sicherheitssysteme zu ermöglichen ist eine direkte, zuverlässige und direkte Kommunikation unmittelbar zwischen den Fahrzeugen vonnöten, die so genannte Fahrzeug-zu-Fahrzeug (engl. Vehicle-to-Vehicle (V2V)) Kommunikation. Hierfür sollen drahtlose Kommunikationstechnologien verwendet werden, wobei aufgrund der nicht klar vorhersagbaren Charakteristika des drahtlosen Übetragungskanals Leistungsgarantien hinsichtlich der Zuverlässigkeit der Kommunikation nicht auf einfache Art und Weise bestimmt werden können.

Um dennoch Verkehrssicherheitsanwendungen auf der Basis von V2V Kommunikation entwerfen zu können ist es notwendig die Systemeigenschaften genau zu kennen und zu verstehen. Die Einsatzbedingungen des Kommunikationssystems sind aufgrund der Kombination verschiedener Eigenschaften des Kommunikationsszenarios sehr herausfordernd: die Anwendungen erfordern einen zeitnahen und zuverlässigen Informationsaustausch, die verfügbare Bandbreite muss ohne zentrale Zugriffskontrolle verteilt genutzt werden, die Daten werden vorwiegend in Form von Broadcast-Nachrichten verschickt, und die mobilen Fahrzeuge sind einer sich ständig verändernden Umgebung ausgesetzt. Diese Eigenschaften führen zu einem Kommunikationsnetzwerk in dem zuverlässige Kommunikation und herausfordernden Bedingungen ermöglicht werden soll. Gegenseitige Beeinflussungen und Interferenzen aufgrund der verteilten Nutzung des beschränkten Kommunikationskanals sind hierbei ein entscheidender Einflussfaktor.

In dieser Arbeit analysieren, modellieren, simulieren und bewerten wir auf IEEE 802.11p basierende Fahrzeug-Kommunikationsnetzwerke unter erwähnten schwierigen Bedingungen. Der Fokus liegt hierbei auf dem Kommunikationsparadigma der periodischen Verbreitung von Broadcast Statusnachrichten durch alle Kommunikationsknoten mit der Intention, dass alle Knoten im geographi-

schen Umkreis die Nachrichten empfangen und sich dadurch über die Position der Fahrzeuge in ihrer Umgebung bewusst sind. Eine solche Art von Kommunikation bildet eine notwendige Grundlage für alle kooperativen Verkehrssicherheistsysteme. Zunächst analysieren wir Anwendungen, die für V2V Kommunikationsnetzwerke vorgesehen sind und leiten ihre Kommunikationsanforderungen ab. Zudem wird ein Überblick über vergangene und aktuelle Forschungsprojekte, Systemarchitekturen sowie Standardisierungsvorhaben gegeben, insbesondere hinsichtlich des Standards IEEE 802.11. Zudem stellen wir Radiowellenausbreitung und ihre Charakterisierung sowie die unterschiedlichen Quellen und Gründe für das Auftreten von Interferenzen vor.

Um periodische lokale Broadcast-Kommunikation analysieren zu können definieren wir die Metrik der "lokalen Broadcasts-Kapazität", in der die Abhängigkeiten zwischen verfügbarer Datenrate, Fahrzeugdichte sowie der Umgebung um einen Knoten, in die die Informationen mit einer definierten Zuverlässigkeit verbreitet werden sollen, formalisiert werden. Zum einen leiten wir analytisch die theoretisch maximal mögliche Kapazität ab, zum anderen führen wir eine "worst case" Betrachtung durch, um eine Orientierung für den Bereich zu haben, in dem die Leistung eines echten Systems zu erwarten ist. Die Ableitung der realen Leistung eines Systems hinsichtlich der lokalen Broadcasts-Kapazität ist jedoch so komplex, dass sich eine analytische Betrachtung als schwierig darstellt.

Ein mögliches Vorgehen das Kommunikationsverhalten weitergehend zu analysieren liegt in der Verwendung von Simulationsstudien, die eine detaillierte Modellierung von physikalischen sowie Interferenzeffekten beinhalten. Wir untersuchen hierfür Modelle, die die Eigenschaften der physikalischen Schicht in V2V Netzwerken nachbilden. In Zusammenarbeit mit Mercedes-Benz Research & Development North America wurden entsprechende Modelle in den Netzwerksimulator NS-2 integriert, der damit eine vollständige Überarbeitung der unteren Kommunikationsschichten erfährt. Diese detaillierte Modellierung und Implementierung ist heute Bestandteil der jeweils verfügbaren Version von NS-2 und erlaubt detaillierte Simulationsstudien.

In der Folge führen wir eine breit angelegte Bewertung mit Hilfe einer Simulationsstudie durch, um die Leistungsfähigkeit von lokaler Broadcast-Kommunikation in V2V Netzwerken zu bestimmen. Alle Knoten innerhalb eines Szenarios versenden periodisch Nachrichten mit Statusinformationen mit der Intention, dass Knoten, die in der geographischen positioniert sind, die Nachrichten empfangen können und so jederzeit über den Zustand und die Position der Knoten in ihrer Umgebung Bescheid wissen. Die Studie deckt einen großen Bereich von Knotendichten, Systemeinflussfaktoren sowie Konfigurationsparametern ab. Die Studie wird anhand mehrerer Metriken sowie einer detaillierten Betrachtung des erfolgreichen bzw. fehlgeschlagenen Paketempfangs ausgewertet, eine Analyse hinsichtlich der wesentlichen Einflussfaktoren sowie der Sensitivität hinsichtlich verschiedener Parameter wird durchgeführt. Des weiteren wird die lokale Broadcasts-Kapazität verwendet, um die Effektivität des zugrunde liegenden Kommunikationssystems aus einer ganzheitlichen Systemsicht zu analysieren. Wir stellen fest, dass das Verhältnis zwischen den simulativ beobachteten Werten und der theoretisch maximal möglichen Kapazität für unterschiedliche untersuchte Knotendichten nur leicht variieren, wenn eine Kombination von Einflussparametern auf das System, z.B. Radiowellenausbreitung, als konstant angenommen wird. Die abgeleiteten Beobachtungen und Werte erlauben die Vorhersage der Systemleistung, wenn viele Fahrzeuge mit entsprechenden Kommunikationsgeräten ausgestattet sein werden.

Diese Arbeit liefert die folgenden wesentlichen Beiträge: eine formale Definition von lokaler Broadcasts-Kapazität, um diese Art von Kommunikation evaluieren zu können, ein Simulationswerkzeug, das auf validierten Modellen aufbaut und ein detaillierte V2V Netzwerkstudien ermöglicht, eine breit angelegte Bewertung der Auswirkungen von Interferenz sowie der Kommunikationsparameter auf die Leistungsfähigkeit von V2V Netzen sowie eine Analyse der erzielbaren Effektivität lokaler Broadcast-Kommunikation in V2V Netzwerken. Es werden grundlegende Einblicke in das System vorgestellt, die zur Optimierung des Systems sowie zur Gestaltung effektiver Algorithmen in V2V Netzwerken verwendet werden können.

Abstract

Vehicle-to-X (V2X) communication, i.e. the direct communication between vehicles and/or the communication between vehicles and stationary road side units, is an envisioned technology that should enable improved cooperative safety systems, advances in traffic efficiency as well as the support of infotainment applications. In order to enable cooperative safety systems a direct, reliable and immediate communication directly between vehicles is mandatory, so called Vehicle-to-Vehicle (V2V) communication. Wireless transmission technologies are used and, due to the unreliable characteristics of the wireless medium, performance guarantees concerning the "quality" of the communication cannot be easily given.

In order to design traffic safety applications on top of V2V communication the system's characteristics have to be known and understood. The operation conditions of the communication system are challenging due to the combination of specific properties that emerge from the scenario under investigation: applications require timely and reliable information delivery, the available bandwidth has to be shared decentralized and without central coordination, data is mainly transmitted as broadcast, and the mobile vehicles are exposed to a varying radio environment. The properties lead to a communication network where reliable communication should be guaranteed under challenging conditions. Mutual interferences due to the shared usage of one restricted communication channel are an important factor.

In this thesis we analyze, model and simulate and assess IEEE 802.11p based vehicular communication networks under the mentioned challenging conditions. Focus is put on the communication paradigm of periodic distribution of broadcast status messages by all nodes with the intent that all nodes in the geographical surrounding receive these messages and thus are aware of the position of vehicles around them. Such type of communication is an essential basis for all cooperative safety systems. We first analyze applications foreseen for V2V communication networks and derive their communication requirements. We also provide an overview of past and current research projects, architectures and standardization efforts, especially IEEE 802.11p. Then, review radio propagation and their characterization and we review different sources and reasons of interference.

In order to evaluate periodic local broadcasts we formalize the dependencies between available data rate, vehicle density, and the area to which information should be provided with a required reliability by the definition of the metric "local broadcasts capacity". We analytically derive the maximum capacity as well as the worst case capacity and thus provide an orientation of the possible range of operation in that real systems are expected to perform. The derivation of the realistic performance of a system with respect to local broadcasts capacity is yet of a level of complexity that can not be covered easily by analytics.

A suitable way to analyze the communication behavior more deeply is the use of simulation studies that include detailed models for physical and interference effects. We investigate on models that cover the specifics of the physical layer in the V2V domain. In collaboration with Mercedes-Benz Research & Development North America, the models were integrated into the network simulator NS-2 that experiences a complete overhaul of the lower communication layers. The detailed implementation has become an integral part of today's distribution of the NS-2 and provides detailed simulation capabilities.

We then provide a broad assessment by a simulation study in order to identify the performance of local broadcast communication in V2V networks. All nodes in a scenario periodically transmit status information messages with the intent that nodes in the geographic surrounding receive the messages and thus become aware of the status of the surrounding nodes. The analysis covers a wide range of node densities, system factors and configuration parameters. The evaluation of the simulations is performed with several metrics and a detailed reception and failure analysis. An analysis on the influence and the sensitivity of system performance is provided. Further, we use local broadcasts capacity to analyze the effectiveness of the underlying communication system from an overall systems point of view. We observe that the ratios between results achieved by intensive simulation studies and the theoretical maximum do not vary much over different node densities when one set of basic system factors, like radio propagation, is assumed. The derived observations and numbers allow the prediction of system performance when the penetration rate among vehicles becomes high.

This thesis provides the following main contributions: a formal definition of local broadcasts capacity to evaluate this type of communication, a simulation framework built on validated models and allowing detailed studies of V2V networks, a broad assessment of the effects of interference and of parameters on the performance of V2V networks and, an analysis on the achievable effectiveness of local broadcast communication in V2V networks. Fundamental insights are presented, that can be used for system optimization and the design of effective algorithms in V2V communication networks.

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Diese Arbeit entstand während meiner Tätigkeit in der Forschungsgruppe Dezentrale Systeme und Netzdienste am Institut für Telematik des Karlsruher Instituts für Technologie (KIT) bzw. der ehemaligen Universität Karlsruhe (TH). Es war mir stets eine Freude in diesem Rahmen meine Forschungen anstellen und das engagierte Forschungsklima in dieser Gruppe mitleben zu dürfen.

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List of Acronyms

AC	access category
ACI	access category index
ACK	acknowledgment frame
AIFS	arbitration inter frame space
AIFSN	arbitration inter frame space number
AP	access point
AKTIV	Adaptive und kooperative Technologien für den intelligenten Verkehr *(project)*
ASTM	ASTM International *(standardization organization)*
AWGN	additive white Gaussian noise
BPSK	binary phase shift keying
BSS	basic service set
BSSID	basic service set identifier
C2C	car-to-car
C2C-CC	Car-to-Car Communication Consortium *(organization)*
C2X	car-to-X communication
CALM	continuous air interface for long and medium distance
CAT	channel access time *(metric)*
CBT	channel busy time *(metric)*
CCA	clear channel assessment
CCH	common control channel
CI	communication interface
CICAS	Cooperative Intersection Collision Avoidance Systems *(project)*
COMeSafety	Communications for Electronic Safety *(project)*
COOPERS	Cooperative Systems for Intelligent Road Safety *(project)*
CRC	cyclic redundancy check
CSMA/CA	carrier-sense multiple access with collision avoidance
CSTh	carrier sense threshold
CTS	clear to send
CVIS	Cooperative Vehicle-Infrastructure Systems *(project)*

CW	contention window
DCF	distributed coordination function
D-FPAV	Distributed Fair Power Adjustment for Vehicular environments *(algorithm)*
DIFS	distributed coordination function inter frame space
DSRC	direct short range communication
DSSS	direct sequence spread spectrum
ECC	Electronic Communications Committee *(organization)*
EDCA	enhanced distributed channel access
EEBL	emergency electronic brake lights
EIFS	extended inter frame space
eSafety	Electronic Safety Initiative *(project)*
ETSI	European Telecommunications Standards Institute *(organization)*
EU	European Union
FCC	Federal Communications Commission *(organization)*
FCS	frame control sequence
FFT	fast Fourier transform
FleetNet	FleetNet *(project)*
FOT	field operational test
GeoNet	GeoNet *(project)*
GPRS	General Packet Radio Service
GPS	global positioning system
IBSS	independent basic service set
ICI	inter-carrier interferences
IEEE	Institute of Electrical and Electronics Engineers *(organization)*
IETF	Internet Engineering Task Force *(organization)*
IFFT	inverse fast Fourier transform
IFS	inter frame space
IntelliDrive	IntelliDrive *(project)*
IP	Internet protocol
ISI	inter-symbol interference
ISO	International Organization for Standardization *(organization)*
iTETRIS	Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions *(project)*
ITS	intelligent transportation systems
KIT	Karlsruhe Institute of Technology *(organization)*

LLC	logical link control
LOS	line of sight
MAC	medium access control layer
NAV	network allocation vector
NoW	Network on Wheels *(project)*
NS-2	Network Simulator 2
OEM	original equipment manufacturer
OFDM	orthogonal frequency division multiplex
OPRAM	OPortunistic-driven adaptive RAdio resource Management *(algorithm)*
PCF	point coordination function
pdf	probability density function
PGR	packet generation rate *(metric)*
PHY	physical layer
PLCP	physical layer convergence protocol
PMD	physical layer medium dependent
PRE-DRIVE C2X	Preparation for driving implementation and evaluation of C2X communication technology *(project)*
PReVENT	Preventive and Active Safety Applications *(project)*
PTR	packet transmission rate *(metric)*
PTRo	packet transmission ratio *(metric)*
QoS	quality of service
QPSK	quadrature phase shift keying
RF	radio frequency
RSU	road side unit
RTS	request to send
SAFESPOT	SAFESPOT *(project)*
SAP	service access point
SCC	Steinbuch Centre for Computing *(organization)*
SCH	service channel
SEVECOM	Secure Vehicular Communications *(project)*
SIFS	short inter frame space
simTD	Sichere Intelligente Mobilität - Testfeld Deutschland *(project)*
SINR	signal to interference and noise ratio
SNR	signal to noise ratio
SME	station management entity
SRR	successful packet reception rate *(metric)*
SRRo	Successful packet reception ratio *(metric)*

TC	technical committee
TCP	transport control protocol
UDP	user datagram protocol
UMTS	Universal Mobile Telecommunications System
USDOT	United States Department of Transportation *(organization)*
UWB	ultra wideband
VANET	vehicular ad-hoc network
V2I	vehicle-to-infrastructure communication
V2V	vehicle-to-vehicle communication
V2X	vehicle-to-X communication
VII	Vehicle Infrastructure Integration *(project)*
VSC	Vehicle Safety Communications *(project)*
VSC-A	Vehicle Safety Communications – Applications *(project)*
WAVE	wireless access in vehicular environments
WG	working group
WILLWARN	Wireless Local Danger Warning *(PReVENT subproject)*
WINNER	Wireless World Initiative New Radio *(consortium)*
WLAN	wireless local area network
WSMP	WAVE short message protocol

1

Introduction

Wireless communication systems have become an essential part of daily life for a big part of the population today. Within the last 10 to 15 years, digital communication networks got popular and common, in particular cellular systems for telephone and data services and wireless local area networks (WLANs) for the flexible connection of end devices. This development towards wireless connectivity is still not finished, but will probably even intensify in the future. The European commission considers the "Internet of things", i.e. the inter-connection of an increasing number of everyday items, as a new paradigm of social development within the next years and supports its development by large action plans. In 2008, J. Rattner (CTO of Intel Corp.) expressed the vision of "1000 radios per person in ten years", what sounds realistic when following the rapid development of smart devices that communicate wirelessly. Due to the enormous number of devices in small space the high degree of mutual influence due to interferences of their transmitted signals is a critical aspect that needs to be analyzed in detail.

An application domain where those visions can become reality in the near future is wireless communication in vehicular traffic networks in order to improve traffic safety and to increase traffic efficiency, vehicle-to-X communication (V2X) networks. The notations car-to-X communication (C2X) and vehicular ad-hoc networks (VANETs) are synonymously used. The "X" emphasizes that either solely vehicles communicate (vehicle-to-vehicle communication (V2V)), or so do vehicles and infrastructure points (vehicle-to-infrastructure communication

(V2I)). For both types of communication similar technologies may be used, and networks combining both are expected. In this thesis we concentrate on direct V2V communication. It is envisioned that by exchanging information directly between vehicles every vehicle should be able to detect vehicles in the surrounding and may calculate the current traffic situation from collected information. Such co-operative cars warn their drivers if necessary, e.g. in case of imminent dangers like possible collisions with other vehicles or appearing obstacles on the road, e.g. road works. The communication therefore has to fulfill highest quality requirements as precise information has to be transmitted with high reliability and short delay under adverse and highly dynamic environmental conditions.

A key building block of V2V communication is the periodic transmission of status information by every individual vehicle. These messages that are often called beacon messages contain information like current position, speed, acceleration and direction of driving. The messages serve as the information basis for the mutual awareness of the vehicles. For vehicles in the close surrounding of a respective transmitter, the reception of beacon messages is of particular importance in order to obtain accurate awareness of the close surrounding. Beacon messages have specific and unusual communication properties that have to be considered. First, beacon messages are transmitted by every equipped vehicle. Second, beacon messages that contain up-to-date information are transmitted in a periodic manner, i.e. several times per second. Third, the messages are transmitted in a broadcast manner and do not have one specific recipient. In consequence, an effective scheme to acknowledge a successful message reception is not easily applicable. Thus, specific methods are necessary to investigate this type of communication that we call local broadcasts communication.

With respect to the mentioned properties it has to be identified how timely and reliable periodic beacon messages can be distributed in the local surrounding of each vehicle. A fundamental and precise knowledge of the systems in use, their behavior and their performance is necessary to evaluate V2V communication and to design systems that work reliable under everyday conditions. **Thus, the goal of this thesis is a comprehensive and precise performance evaluation of periodic local broadcast communication in V2V communication networks.** Of particular interest is the scalability of huge and dense networks. It turns out that the hidden terminal problem is particularly relevant as it causes interferences during the reception of messages. We discuss the analysis of consequences of mutual interference on the performance of V2V networks and consequently on their potential. Thus, such networks are analyzed with a focus on the possibilities and limitations that the communication mechanisms and the physical characteristics provide for the special type of data traffic that is exchanged.

1.1 Objectives and contributions

This thesis follows multiple strategies to answer the question of the performance capabilities of V2V communication networks from different perspectives. The approaches are assessed with respect to their applicability for a performance evaluation. While *analytical* approaches show fundamental dependencies they typically have to make simplifying assumptions in order to remain tractable, but allow the evaluation of systems under idealized conditions. A central role have the *models* that are taken to describe the system and its environment. If models are implemented in software they can be used for *simulation* studies that provide a valuable way for further investigation. It is yet required that the simulation models are selected adequately with respect to the problem and that the models are validated. Further, the *assessment* of the problem by simulation runs and the evaluation requires a precise methodology. In this thesis the mentioned approaches are discussed such that two main objectives are reached first: a procedure for modeling V2V communication networks is provided, i.e. an appropriate selection of applicable models that respect the influences coming from the wireless communication channel, in particular interference, is extracted. Second, a broad performance evaluation is done identifying the relevant parameters and mechanisms in V2V communication networks and their influence on network performance.

In Figure 1.1 the structure of this thesis is illustrated graphically. Each of the chapters discusses specific questions and has its specific objective. The answers found in each chapter form the contributions of this thesis and generate the input for the subsequently following chapter. The thesis starts with an introduction to V2X networks and according projects, applications, and research and standardization activities in Chapter 2, followed by the presentation of relevant related work with respect to radio propagation and interference characteristics and modeling in Chapter 3. In each of the subsequent Chapters 4, 5 and 6, a combination of two of the four domains analysis, modeling, simulation, and assessment is discussed. Chapter 4 takes a theoretical point of view on the analysis and modeling of V2V communication, while in Chapter 5 the topic is discussed from the modeling and simulation perspective. In Chapter 6 the simulation approach is practically applied for assessment of the communication system. In Chapter 7 the conclusions from the previous discussions are drawn. The contributions achieved within the course of this thesis are briefly described in the following.

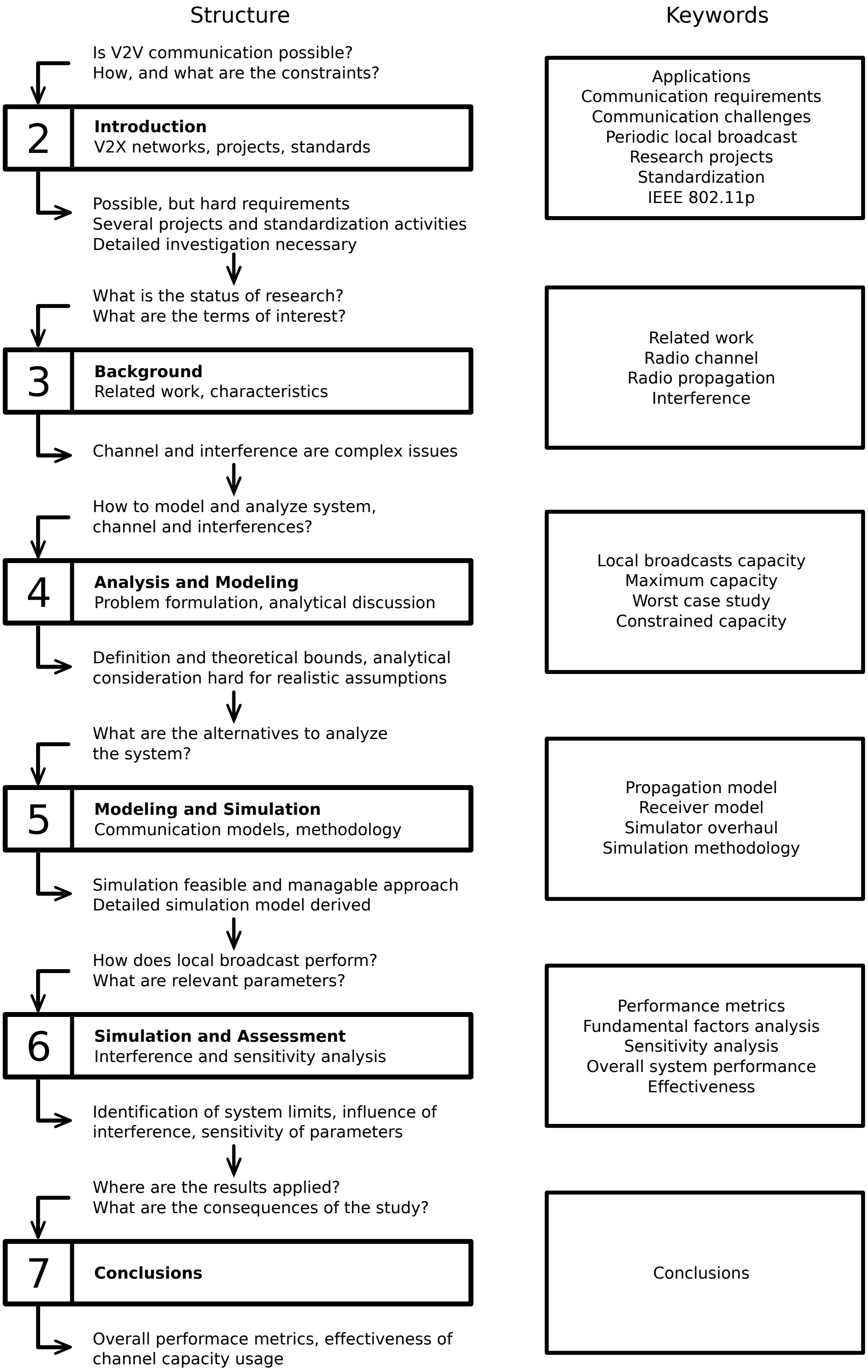

Figure 1.1: Structure of this thesis: objectives, content and main contributions of each chapter as well as inter-dependencies between the chapters.

V2V communication network requirements, capabilities and limitations (Chapter 2). In this chapter vehicle-to-vehicle communication networks are reviewed in a top-down approach. First, use-cases and possible application scenarios are identified. Exemplary applications are described and requirements for the communication system are derived. The periodic local broadcast transmission of status information to and by all vehicles is identified as type of communication that requests special attendance due to its specific characteristics and its sensitivity to interference effects. The chapter provides a review on already finalized, current and planned research projects, standardization activities and market introduction plans, such that an overview of the state of the art of V2V communication is provided.

Background and related work (Chapter 3). In this chapter related work is reviewed. In particular, the characteristics of the radio channel are described and reviewed and different sources of interference are identified. Then, the challenges of wireless communication for vehicular networks are extracted, in particular interferences caused by the severe and rapidly changing environmental influences and interferences caused by imperfect synchronization of transmissions. The discussion shows the necessity of exploring requirements as well as limitations in detail and of analyzing the communication system in depth.

Analysis of V2V communication performance on periodic local broadcasts (Chapter 4). The communication scenario is considered analytically and local broadcasts capacity is introduced. The limited communication channel restricts the amount of information that can be transmitted per period of time, yet, the achievable capacity should serve the communication requirements of the applications. Thus, the influencing factors are used to develop a capacity definition for periodic local broadcast communication: the data rate of the communication system, the vehicle density, the range of awareness requested by applications, and the probability of successful packet reception within the awareness range.

A theoretic maximum local broadcasts capacity is derived and provides an upper capacity bound with respect to the influencing factors. A worst case study is presented as well, and the worst case local broadcasts capacity is derived from the study. Further, local broadcasts capacity is discussed under the assumption of additional constraints. Although the theoretical considerations provide achievable capacities for extreme cases it is hard or even infeasible to analytically derive the achievable capacity under a model that represents the real network performance due to strong interdependencies.

Simulation models that appropriately represent IEEE 802.11p based V2V networks and the related physical phenomena (Chapter 5). A simulation models for vehicle-to-vehicle communication and according parameters are identified and implemented to be used in simulation studies. The models represent communication following the standard currently being developed for V2V communication, IEEE 802.11p, and allow simulations close to reality. Therefore, particularly the precise modeling of physical characteristics is crucial, as all higher protocol layers and the applications can be severely influenced from inaccuracies on the physical layer. The models provide the basis for detailed and precise performance studies by simulation.

The challenging properties of the communication channel due to mobility and multi-path propagation are modeled by probabilistic radio propagation models. Interference effects in the receiver units resulting from parallel reception of multiple packet transmission are modeled by a cumulative noise model. The individual consideration of the different parts of a data packet during its reception, together with the consideration of the signal to interference and noise ratio (SINR) allows precise decisions on packet reception success or failure. The medium access method is modeled precisely according to IEEE 802.11p. The models combined with their parameterization create the scenario definition that is used in the further discussions. Models are validated by literature review, tests, face validation and cross-validation with other simulation models.

Model integration into the Network Simulator 2 (NS-2) and simulation methodology and tools for the analysis of the performance of V2V communication networks (Chapter 5). The Network Simulator 2 (NS-2) [NS-2] is overhauled with the models mentioned before in a structured way and was thus improved with respect to accuracy due to the precise modeling. The structure of medium access and physical layer allows easier traceability, code review and verification against the specification described in the standard documents. The improvements are part of the officially released NS-2 versions since March 2008. The simulation models were developed in collaboration with Mercedes-Benz Research & Development North America.

Simulation studies are supported methodically by a framework that includes all necessary components to perform according studies. The simulation platform consists of a tool to generate mobility movement patterns, the improved network simulator described before, and an evaluation methodology that allows in depth studies by the definition of per-packet reception categories as well as performance analysis by a set of defined metrics.

Assessment of reception and interference for periodic local broadcast communication (Chapter 6). The V2V communication system performance is analyzed for several densities and under a multitude of system modeling factors and a lot of configuration parameters in order to gain insights into reception reliability, timeliness and scalability. The detailed analysis of different reception categories shows the impact of interference in particular under dense network conditions and the necessity of interference mitigation. A feature of reception hardware is the capture capability that allows to process packets with strong reception power even if another reception process has already been started. Is is shown that making use of the capture capability is a successful way to improve local broadcast performance in close distances and mitigate interferences.

Sensitivity analysis of communication parameters (Chapter 6). Sensitivity analysis studies are performed in order to indicate the influence of application and communication specific parameters on communication quality. It is shown that the adaption of transmission power and the rate of status message generation and packet sizes provide potential to improve the simulation performance with respect to reception rates.

Overall system analysis by the analysis of simulated local broadcasts capacity (Chapter 6). Overall system performance analysis is performed in order to identify the local broadcasts capacity that a communication system achieves when realistic simulation models are applied. Obtained results are compared to the theoretic maximum capacity and the ratio provides a measure for the effectiveness of capacity usage by the simulated systems. Derived regularities provide potential to be used in further studies, system optimization and algorithm design.

Parts of the contributions of this thesis have been previously presented in the publications listed below.

- F. Schmidt-Eisenlohr, M. Torrent-Moreno, T. Tielert, J. Mittag, H. Hartenstein: *Cumulative noise and 5.9 GHz DSRC extensions for ns-2.28*, in Technical report 21, Fakultät für Informatik, Universität Karlsruhe (TH), Oct. 2006, http://digbib.ubka.uni-karlsruhe.de/volltexte/1000005768 [Schmidt-Eisenlohr et al. 2006b]

- M. Torrent-Moreno, S. Corroy, F. Schmidt-Eisenlohr, H. Hartenstein: *IEEE 802.11-based one-hop broadcast communications: understanding transmission success and failure under different radio propagation environments*, in Proceedings of the ACM International Conference on Modeling Analysis and Simulation of Wireless and Mobile Systems (MSWiM), pp. 68–77, Oct. 2006 [Torrent-Moreno et al. 2006]

- F. Schmidt-Eisenlohr, M. Torrent-Moreno, J. Mittag, H. Hartenstein: *Simulation platform for inter-vehicle communications and analysis of periodic information exchange*, in Proceedings of the IEEE/IFIP Annual Conference on Wireless on Demand Network Systems and Services (WONS), pp. 50–58, Jan. 2007 [Schmidt-Eisenlohr et al. 2007]

- M. Killat, F. Schmidt-Eisenlohr, H. Hartenstein, C. Rössel, P. Vortisch, S. Assenmacher, F. Busch: *Enabling efficient and accurate large-scale simulations of VANETs for vehicular traffic management*, in Proceedings of the ACM International Workshop on Vehicular Ad hoc Networks (VANET), pp. 29–38, Sep. 2007 [Killat et al. 2007]

- Q. Chen, F. Schmidt-Eisenlohr, D. Jiang, M. Torrent-Moreno, L. Delgrossi, H. Hartenstein: *Overhaul of IEEE 802.11 modeling and simulation in ns-2*, in Proceedings of the ACM International Conference on Modeling, Analysis, and Simulation of Wireless and Mobile Systems (MSWiM), pp. 159–168, Oct. 2007 [Chen et al. 2007]

- A. Kuntz, F. Schmidt-Eisenlohr, O. Graute, H. Hartenstein, M. Zitterbart: *Introducing probabilistic radio propagation models in OMNeT++ mobility framework and cross validation check with ns-2*, in Proceedings of the International Workshop on OMNeT++, Mar. 2008 [Kuntz et al. 2008]

- F. Schmidt-Eisenlohr, H. Hartenstein: *Vernetzte Fahrzeuge – Kommunikationsstrategien und Simulationsmethodik*, in J. Sieck (editor), M. Herzog (editor) Wireless Communication and Information: New Technologies and Applications, pp. 195–205, vwh Verlag, ISBN: 978-3-940317-27-8, Apr. 2008 [Schmidt-Eisenlohr & Hartenstein 2008]

- F. Schmidt-Eisenlohr, M. Killat: *Vehicle-to-vehicle communications: reception and interference of safety-critical messages*, in it – Methods and Applications of Informatics and Information Technology, vol. 50, nr. 4, pp. 230–236, Jul. 2008 [Schmidt-Eisenlohr & Killat 2008]

- O. Jetter, M. Killat, J. Mittag, F. Schmidt-Eisenlohr, J. Dinger, H. Hartenstein: book chapter on *Simulative analysis of vehicle-to-X communication considering traffic safety and efficiency* in W. E. Nagel, D. Kröner, M. Resch (ed.): *High Performance Computing in Science and Engineering '09*, Springer, Dec. 2009, ISBN 978-3-642-04664-3 [Jetter et al. 2009]

- J. Mittag, F. Schmidt-Eisenlohr, M. Killat, M. Torrent-Moreno, H. Hartenstein: *MAC Layer and Scalability Aspects of Vehicular Communication Networks* in H. Hartenstein, K. Laberteaux (ed.): *VANET - Vehicular Applications and Inter-Networking Technologies*, John Wiley & Sons, ed. 1, Jan. 2010, ISBN 978-0-470-74056-9 *(to appear)* [Mittag et al. 2010]

2

Overview on vehicle-to-vehicle communication networks

This chapter gives an overview of envisioned applications for inter-vehicle communication and projects in which the applications are considered. Then, exemplary applications are investigated and their communication requirements identified. Subsequently, we extract the communication challenges to be expected. In the following, we give an introduction to the technical fundamentals that underly vehicular communication and show the current status of worldwide standardization efforts, in particular IEEE 1609 and IEEE 802.11p. We finally concentrate on the research questions of this thesis: how can the application requirements be mapped to a communication system respecting the challenges given by wireless communication and related interferences? How can the communication performance be analyzed and evaluated? How does a system have to be designed and configured such that the requirements of applications are fulfilled, that allow the application to work reliably? Under which conditions is the communication system capable to fulfill the requirements? We show that the investigation of interference effects is an important aspect when considering the performance of V2V communication networks. We show how well communication systems behave when intensive broadcast communication due to the exchange of status messages is considered.

The chapter is organized as follows: in Section 2.1 past and current research projects and activities worldwide are presented. Section 2.2 presents use cases and applications of intelligent transportation systems (ITS), and in Section 2.3 the corresponding requirements are derived with focus on safety applications. A detailed consideration of a selected application scenario is provided: emergency electronic brake lights (EEBL). Further, the challenges that have to be solved are summarized before current standardization activities are presented in Section 2.4. We concentrate on the architectures that make use of the allocation of dedicated bandwidth for direct short range communication (DSRC) in the United States in 1999, and in Europe in 2008. Proposed architectures will be described in Section 2.4.1, and the promising standardization activities for the IEEE 1609/802.11p communication stack as well as spectrum allocation are discussed in the subsequent Sections 2.4.2 and 2.4.3. The overview on V2X activities is concluded in Section 2.5.

Before presenting details we first want to provide a short overview on related literature providing an overview on the field of V2V communication. Possible application types are identified in [Jakubiak & Koucheryavy 2008] and economic issues and market introduction are discussed. Ongoing world-wide research activities are shown, and the authors' points of view on the major open research challenges is given: wireless access technologies, spectrum issues, broadcasting and message dissemination, routing issues, power management, security and privacy, and VANET modeling and simulation. In this work, most of the mentioned issues are also intensively discussed. In the survey [Hartenstein & Laberteaux 2008] the current development in vehicular networks with a focus on WLAN based communication networks are presented. Applications, main challenges, communication specific issues as well as protocols and security considerations are discussed, with the conclusion that standardization has to be finalized, application requirements to be identified and the impact of applications on safety and efficiency to be shown. [Sichitiu & Kihl 2008] give a survey over the research field as well, including an exhaustive list of references to research activities and related projects up to the year 2006. The authors conclude that, despite of the potential of such networks, there are still a lot of challenges that have to be tackled. A more specific discussion on the process of standardization of vehicular communication is given by [Jiang et al. 2006]. The paper discusses the procedure of WLAN adaptation for vehicular networks and gives insights to the main subjects of discussion. Finally, the book [Hartenstein & Laberteaux 2010] (to appear in January 2010) will provide a detailed introduction and discussion of many aspects of V2V communication and describes the state-of-the-art with respect to applications, networking and communication technologies. A detailed description of current research and standardization is provided as well

2.1 Research projects

Several projects worldwide have investigated the improvement of transportation systems with respect to the positive effect on traffic safety and traffic efficiency. In recent years, the specific role of V2X communication came into focus and broadened the research domain to the interaction of vehicles and infrastructure. Before, these domains were often treated separately: while from infrastructure side adaptable traffic telematics applications were introduced (e.g. variable message signs for speed and number of parking lots, or adaptive traffic lights for traffic flow optimization), on the vehicle side, electronic systems were introduced to improve passenger safety, the controllability of the vehicle in critical situations, or navigation systems. The possibility to interact via wireless communication between infrastructure and vehicles, as well as directly between vehicles, allows to develop completely new application scenarios where cooperation of the different entities may be achieved. We now first present projects where such possible applications were discussed, before deriving the communication challenges and then looking at the technical systems that should provide the necessary communication requirements.

Mainly with respect to traffic safety a major effort was provided by the "Vehicle Safety Communications (VSC)" project [WWW VSC 2006] in the United States, that was supported by the United States Department of Transportation (USDOT) and performed by a consortium of seven car manufacturers. Within the project, 34 safety-related and 11 non-safety related potential application scenarios were described, and a possible system design as well as communication requirements were determined. Further, the application scenarios were categorized and evaluated with respect to their potential of probably being realizable in near, middle or long term future.

As a first result, eight representative near-term and mid-term applications were extracted for which the communication requirements were derived: traffic signal violation warning, curve speed warning, emergency electronic brake lights, pre-crash sensing, cooperative forward collision warning, left turn assistant, lane change warning, and stop sign movement assistance. In Section 2.3.1 we will discuss the emergency electronic brake lights (EEBL) application in detail. The VSC project also investigated several wireless communication technologies that could be potential candidates as a system's basis, including direct short range communication (DSRC), 2.5/3G cellular systems, Bluetooth, radar systems or ultra wideband (UWB) communication. As specific DSRC solutions look most promising, real world field testing was performed that provided first insights into the system capabilities.

The USDOT and the VSC 2 consortium consisting of five car manufacturers work on a subsequent project, “Vehicle Safety Communications – Applications (VSC-A)” [WWW VSC-A]. The research is continued with the goal of proving that communication-based vehicle safety systems, combined with vehicle positioning, can actually improve the existing safety systems in vehicles. The project concentrates on identifying the major shortcomings that affect the rapid deployment of according safety systems and tackling them by defining according systems and contribute to the standardization initiatives.

The IntelliDrive project [WWW IntelliDrive] in the United States, formerly called Vehicle Infrastructure Integration (VII) project, considers the communication between vehicles and infrastructure. Different applications like in-vehicle signage, electronic payment or traffic light indication were developed and installed as real testbeds in California and Michigan. The project shows that in principle, V2I communication is feasible and could enable according applications in the vehicles. The “Cooperative Intersection Collision Avoidance Systems (CICAS)” project [WWW CICAS] in the United States investigates the avoidance of collisions at intersections by cooperation over wireless communication capabilities.

In Europe, within the Framework Programmes 6 and 7 several projects were initiated with respect to the exploration of ITS and their application. A short overview of the different projects and their objectives should be given. In 2002, the European Union (EU) started the Electronic Safety Initiative (eSafety), that has the goal of improving traffic systems by electronic systems. In the 6th Framework Programme of the European Commission, four integrated projects were started in 2006: PReVENT, COOPERS, SAFESPOT and CVIS. The projects all considered ITS solutions, but from different perspectives and for different intents of application.

Within the “Preventive and Active Safety Applications (PReVENT)” project [WWW PReVENT], the focus lies on autonomous electronic systems in the vehicles to improve safety, the integration of intelligent sensor systems like radars or lidars. However, the focus was not put on the exchange of this information with other vehicles. An exception is the sub-project “Wireless Local Danger Warning (WILLWARN)” [WWW WILLWARN] in which direct communication between vehicles was used in order to extend the driver’s horizon and warn in case that dangerous situations have to be expected. The project “Cooperative Systems for Intelligent Road Safety (COOPERS)” [WWW Coopers], instead, makes intensive use of V2I communication to improve traffic telematic systems and bases on the CALM architecture presented below. The vehicles provide information to the infrastructure that, in a centralized fashion, provides traffic management information. The “Cooperative Vehicle-Infrastructure Systems (CVIS)” project

[WWW CVIS] also makes use of V2I communication, but with a stronger focus on safety applications. It also uses the CALM architecture. The "SAFESPOT" project [WWW Safespot] focuses on cooperative safety systems, where direct V2V communication plays a central role. The projects mainly concentrated on identifying feasible applications, exploring the basic technologies and on setting up test scenarios to show that the intended way of V2X communication is basically feasible.

In the 7th Framework Programme of the European Commission, again several projects related to vehicular communications were initiated. In 2008, the project "Preparation for driving implementation and evaluation of C2X communication technology (PRE-DRIVE C2X)" [WWW PRE-DRIVE C2X] was started with the intent to perform all necessary preparations for large field operational tests (FOTs). Within the work, possible application scenarios have to be selected and evaluated and available system components collected and identified. Out of these activities a system design and a strategy for FOTs is determined.

Several other European projects focus on more specific aspects of V2X systems. The "GeoNet" project [WWW GeoNet] focuses on providing protocol specifications that allow a geographical dissemination of information in a vehicular network, thus, a protocol-centric network's point of view is taken. The "Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions (iTETRIS)" project [WWW iTetris] works on providing large-scale simulation capabilities in order to evaluate the effect of traffic management applications and compares the results with the ones achieved at a testbed in Bologna, Italy. The "Secure Vehicular Communications (SEVECOM)" [WWW Sevecom] project has its focus on the security and privacy aspects of V2X communication and provides according strategies and protocols.

Several national projects have caused wide attention due to their promising results as well. In Germany, the "FleetNet" project [WWW FleetNet] was providing a first feasibility analysis with respect to V2V communication. The cooperation of car manufacturer, suppliers and academia proved the feasibility of such communication with a small test fleet. In the subsequent "Network on Wheels (NoW)" [WWW NoW] project the focus was put on the development, design and optimization of communication protocols that support safety applications. Again, the feasibility was shown by both simulations and test bed deployment in a final demonstration. Different types of applications and their realization (traffic management, active safety, and cooperative cars) were also investigated within the project "Adaptive und kooperative Technologien für den intelligenten Verkehr (AKTIV)" [WWW Aktiv]. Currently, the project "Sichere Intelligente Mobilität - Testfeld Deutschland (simTD)" [WWW SimTD] makes preparation steps to apply the communication techniques in a huge field test within the Rhein-Main region, where applications, protocols, and communication techniques will be tested at a larger scale.

Platforms and room for coordination, cooperation and visibility of the different projects is provided by several initiatives and organizations. The project "Communications for Electronic Safety (COMeSafety)" [WWW COMeSafety] gives the possibility to collect the results of the different individual projects and gives room to discuss them. Another organization is the "Car-to-Car Communication Consortium (C2C-CC)" [WWW C2C-CC] that consists of the major European car manufacturers (OEMs), several industrial automotive suppliers, and several research members, mainly from academia. The C2C-CC coordinates the different interests and supports the further development and standardization of V2X technology with several working groups (WGs). Further discussion of architectures, technologies and standardization achieved will be given in Section 2.4.

2.2 Use cases and application scenarios

As it was shown in the last section in current research, V2X communication networks are intensively studied. The application scenarios for which the networks should be applied are often categorized into three different domains: traffic safety applications, traffic efficiency applications and infotainment applications. We will discuss the different categories in the following and give examples of possible envisioned applications.

Several projects have derived collections of possible applications of vehicular communication for the different domains. As already mentioned in the last section, the VSC project in the United States was one of the first project activities where many application scenarios were described. Recently, the PRE-DRIVE C2X project collected possible applications and their requirements from the various project activities that were conducted over the years. In the following a brief overview of possible applications and their intention will be given.

2.2.1 Applications for traffic safety

Traffic safety applications have the goal to further improve the safety of vehicular traffic, i.e. reduce the number of dangerous situations, accidents, and road fatalities. During the history of developing vehicles this goal always was a central driving force for inventions. Nowadays, vehicles are equipped with many systems and technologies that improve traffic safety passively and actively. Seat belts, airbags and the energy absorbing construction of the vehicle reduce the risk of injury when an accident happens. Some modern vehicles are already equipped with automatic braking systems that enable an emergency brake to reduce the consequences of a crash. Electronic systems like anti-blocking systems (ABS) or electronic stability control (ESP) are standard equipment in new vehicles today. They allow a better control of the vehicle in critical situations and help to avoid an accident. All systems have in common that the information necessary to actively use the systems is determined locally by sensors in the vehicle that measure several physical values like distances, speed or acceleration or environmental influences like temperature, rain or visibility.

Traffic safety systems may be further improved if additional information would be available. Vehicles in the near surrounding can serve as sources for such additional information: as the other vehicles also collect sensor data for their own safety systems, sharing such data can give additional input to the safety system. The exchange of vehicle position, speed, acceleration and other status information among all vehicles in the surrounding leads to cooperative awareness, i.e. each vehicle can extract its own perspective on the current traffic situation. From such a view, and in conjunction with other available sensor data, dangerous traffic situations that may lead to an accident can be detected earlier. The additional explicit information on critical situations is used to either inform and warn the driver of the vehicle in an appropriate way, or to directly influence the safety system. Promising examples for active and cooperative traffic safety systems are warnings on approaching possibly dangerous traffic situations like the end of a traffic jam, a broken vehicle, strong braking or changing road conditions. Support, aid and warnings when performing specific driving maneuvers like a lane change or turning to the left or right can also be provided.

The “emergency electronic brake lights (EEBL)” are one example of a possible safety application. The goal of such a safety application is the avoidance of rear-end collisions. A vehicle that, due to a safety critical reason, has to brake strongly, informs other traffic participants of this change in its driving status by transmitting according information on the wireless communication system. The information is contained within a specific safety message. By using wireless communication the information may earlier reach other traffic participants that follow the braking vehicle compared to the time that is typically necessary to visually recognize the situation. The EEBL application was intensively evaluated in the VSC project. In [Zang et al. 2008] a protocol to support the particular application was developed and it was shown that V2V communication can help to reduce rear-end collisions. A detailed discussion on EEBL will be given in Section 2.3.1.

Another approach to avoid rear-end collisions is called “Cooperative Forward Collision Warning”. Here, the vehicles periodically transmit their current driving status in beacon messages such that all vehicles in the surrounding can achieve this information. By combining all input information and relating them to the own current driving status including the position, a vehicle may warn its driver of a possible collision that may be avoided if the vehicle immediately brakes. The difference to the application described before lies in the fashion of providing the information: while, in the first scenario, explicit messages are transmitted in case of a specific event (e.g. strong braking), such information is provided periodically by all vehicles, not being triggered by a specific event. There is a difference in the way of handling such information: while, in the first case, a vehicle only has to determine whether it is affected by the warning message transmitted, in the second case the vehicle has to derive the traffic situation from the information provided. Additional information from local sensors has to be taken into consideration as well.

Another group of applications related to traffic safety are warnings with respect different types of driving maneuvers, e.g. overtaking, lane changing, or turning left/right. For these situations, a warning message supports the driver in cases where it is not safe to continue proceeding with the maneuver. For these types of applications cooperation of the different vehicles may be necessary.

Applications that support traffic safety at intersections form another type. Here, communication is used to inform the driver of the possible danger of crashes at intersections. The applications may be coupled with existing infrastructure, like traffic signs and traffic lights, but in an cooperative way such type of safety applications may also be performed directly between the vehicles.

2.2.2 Applications for traffic efficiency

Traffic efficiency applications focus on the goal of increasing the efficiency of the traffic system with respect to different perspectives like saving fuel, travelling times, emissions, or traffic flow. Existing systems often collect the necessary information to increase traffic efficiency by stationary installations like inductive loops or cameras. The traffic is influenced by adaptively changing the phases of traffic lights or by using dynamic traffic signs. Inside the vehicles traffic efficiency is supported e.g. by navigation systems that propose driving directions to the driver.

V2X communication offers several opportunities to further improve traffic efficiency. The possibilities range from gathering up-to-date traffic status information from individual vehicles (Floating Car Data) over route planning for every individual vehicle to possibilities to harmonize traffic by transmitting speed assignments or traffic light phase information. Traffic efficiency applications typically involve V2I communication with the infrastructure and the back end networks. An important field is the better support of traffic management centers with the necessary information on current density and speed of vehicular traffic at locations where other types of sensors like inductive loops are not installed. Advanced applications deliver feedback to the drivers and provide optimized route advisory based on the overall traffic situation or give early information on upcoming problematic traffic incidents.

The advantage of V2X communication in the traffic efficiency domain lies in the connection of information that is available to traffic authorities with the specific information of the individuals participating in the traffic system. Currently, the huge problem of traffic authorities lies in the fact that the drivers can only be informed of the current situation either with considerable delay (e.g. by traffic information broadcasted by radio stations) or only at fixed locations (e.g. by variable traffic signs). Thus, V2X communication systems can provide information covering the whole road network, and the drivers can be informed instantaneously, individually, and at every location – given the wireless communication system provides the necessary geographical coverage.

2.2.3 Applications for infotainment

The third group of possible applications over V2X communication covers information and entertainment applications. The passengers of a vehicle could be informed of nearby services, restaurants, companies or touristic sights. Connections to the Internet can be established by using V2I communication, allowing typical communication services like web browsing, mail or chat.

Promising applications cover charging services, e.g. on toll roads, that would allow automatic tolling without having to stop. In difference to today's situation where every country establishes its individual tolling systems, e.g. Toll Collect for trucks on German highways, a unified communication approach could replace the individual systems in the future.

Further applications are improved services for navigation systems, e.g. by providing updated maps, up-to-date traffic information or correction signals for the global positioning system (GPS) in order to improve the accuracy of vehicle localization. Another possible application considers improved service maintenance and software updates for the vehicle, either in the garage, or even outside.

It is important to consider privacy aspects of V2X communication. As the widespread of applications shows, such communication systems can, if not secured appropriately, lead to a perfect surveillance of vehicles and their drivers, what clearly is a very critical issue with respect to the privacy concerns of the users. The trade-off between providing and gaining improved and individual information and staying anonymous to some degree is not easy to clarify and needs further consideration and discussion.

2.3 V2X communication requirements & challenges

After having provided a brief overview on different types of applications that make use of V2X communication we will now have a closer look on the requirements that have to be fulfilled such that the applications can provide their expected service. Due to the variety of applications the related requirements differ for individual applications. First, in a rough way the requirements are discussed following the application categories introduced in the last Section 2.2. Then, we will consider selected applications in more detail. In the following we discuss applications that support the driver during driving with respect to traffic safety and efficiency,. However, we always assume that the driver is the responsible person for driving, thus we do not discuss requirements that have to be fulfilled if automatic driving should be enabled.

Traffic safety applications require fast and reliable information on the current traffic situation and on potential hazards in the near surrounding. The information updates of any individual vehicle need to be provided to the vehicles in a specific, "safety-relevant" surrounding. For safety applications the communication requires the periodical exchange of broadcast messages. The probability that the messages can be successfully received within the safety-relevant surrounding needs to be high and the number of information updates has to be high as well. Additionally, the delay from the generation of a message to its reception has to be very short. The final report of the VSC project [WWW VSC 2006, p. 18] provides a preliminary estimate on the communication requirements that have to be provided for traffic safety applications: messages of a size of a few hundred bytes (200 – 500 byte) are periodically transmitted several times per second (every 100 ms) as well as being transmitted on an event-driven basis. The typical communication type is one-way in a point-to-multipoint fashion, with the reception nodes positioned up to a distance of some hundred meters (50 – 300 m) and a maximum acceptable latency of 100 ms, sometimes even 20 ms.

The traffic safety application requirements obtained in the VSC and the VSC-A project, as well as the ones obtained in the European projects have been put in an informational Internet Engineering Task Force (IETF) Internet draft and submitted for further discussion, see [Karagiannis et al. 2009]. More detailed communication requirements for some scenarios will be extracted below in Section 2.3.1.

Traffic efficiency applications typically have less stringent restrictions than traffic safety applications with respect to delay requirements and the periodicity of messages. Also, messages are typically not exchanged directly between vehicles, but the communication is either provided by infrastructure points to the vehicles, or vehicles provide information to an infrastructure point, thus V2I communication is the major communication type. In case that an infrastructure point cannot be reached directly by a vehicle or vice versa, it is envisioned that vehicles geographically positioned on the way of message distribution store and forward the messages. Special routing protocols are necessary for such relaying schemes. It is expected that messages of variable size are regularly transmitted by the infrastructure points (e.g every 1-2 s) to the vehicles within a certain street segment (e.g. 1000 m long), and the message delay is not of major importance. In the other direction, vehicles may transmit messages on a regular basis (e.g. every 10 s) to an infrastructure point within distance.

2.3.1 Examples from traffic safety

We analyze one specific application in more detail in the following to derive its requirements to the communication system. As mentioned in Section 2.2.1 one example for a traffic safety application is emergency electronic brake lights (EEBL) that supports the avoidance of rear-end collisions. The application is selected here for deeper investigation due to several reasons. First, the application can be built upon pure V2V communication and thus presents an example how information and cooperation directly between vehicles can be provided. Second, EEBL was one of the first applications that was actually tested in reality and shown to work in principle, see [Shulman & Deering 2007, p. 8-9]. As an internal project in the scope of the VSC project, several of the consortium partners practically set up the EEBL application by defining communication system, message formats and algorithms and practically testing the system in different variants.

In case of strong braking of a vehicle, an according warning message is transmitted, so that subsequently following vehicles can react early enough, i.e. before an accident happens. We show the necessity that specific communication requirements are fulfilled in order to reach a safety advantage by V2V communication. We assume a scenario of three vehicles that follow each other and that all drive with a velocity of $v = 30$ m/s (108 km/h). The vehicles have a distance of $d = 50$ m between each other, what reflects the statutory required distance at that speed. As a rule of thumb, the minimum safety distance in [m] should not be smaller than half the value shown on the tachometer, expressed in [km/h]. The information contained in explicit messages can also be part of periodically transmitted beacon messages in case the message rate is high enough.

A similar setup is analyzed in [Sepulcre & Gozalvez 2007] where communication parameters are optimize in order to avoid a collision at an intersection. As such collision avoidance may cause a strong braking, a situation similar to the one described here could occur as well: while the collision at the intersection is avoided, rear-end collisions may happen instead. Thus, strategies are discussed with which the collision at the intersection as well as chain collisions can be avoided by including vehicle dynamics in the calculation optimal communication parameters.

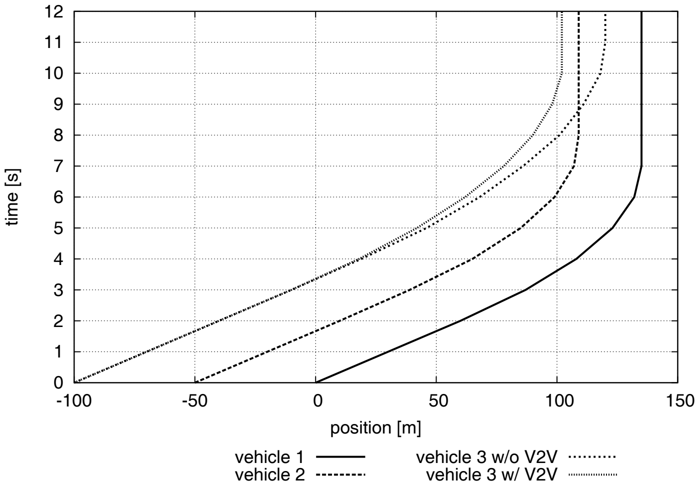

Figure 2.1: emergency electronic brake lights (EEBL) application: space-time-diagram of the three vehicles. The third vehicle can avoid a collision in case timely and reliable communication provides braking information of vehicles driving in front earlier.

For the example setup and under simplified assumptions with respect to vehicle dynamics (we assume a constant deceleration ratio here starting instantaneously when the brake is used), Figure 2.1 shows the trajectories of vehicles of a potential traffic situation in a space-time-diagram. The position of vehicles is shown on the x-axes, while the elapsed time is shown on the y-axis. We examine the following situation: at time $\tau_1 = 2.0\,\mathrm{s}$ the first vehicle strongly brakes with a deceleration rate of $a_1 = 6.0\,\mathrm{m/s^2}$. In order to perceive the situation the second driver needs a reaction time of $\rho = 0.8\,\mathrm{s}$, thus he starts braking at $\tau_2 = 2.8\,\mathrm{s}$, also with a deceleration of $a_2 = 6.0\,\mathrm{m/s^2}$. If we assume that the driver of the third vehicle cannot directly see the braking lights of the first vehicle and needs the same amount of time to react, he would start braking at time $\tau_3 = 3.6\,\mathrm{s}$. If we further assume that the vehicle is heavier, or has worse brakes, and thus a deceleration rate of only $a_3 = 4.0\,\mathrm{m/s^2}$, a collision of vehicles 2 and 3 would occur.

If, in contrast, the driver of the third vehicle would have been earlier informed that the first vehicle starts braking strongly, the collision could have been avoided. If we again assume a reaction time of $\rho = 0.8\,\mathrm{s}$, and if the information of strong braking reaches the driver of the third vehicle within $\delta = 0.2\,\mathrm{s}$ after the maneuver was initiated, the collision would have been avoided, see the second curve (with V2V) of vehicle 3 (start of braking at $\tau_3' = 3.0\,\mathrm{s}$). A longer delay of $\delta' = 0.4\,\mathrm{s}$, in contrast, would not have resolved the dangerous situation and a collision would have happened. As we can observe here, V2V communication is capable to provide information earlier to drivers and thus can support the avoidance of collisions. Yet, the the information of danger has to be reliably provided and with a maximum delay.

From the example we observe that providing information earlier to the drivers of the following vehicles increases the probability to avoid a collision. The usage of V2V communication technologies enables such earlier information. When the first vehicle senses its strong deceleration it could have either sent out an according warning message or included this information in its next periodic status message. From the example we observe that the reliability of message delivery has to be high and that a low corresponding latency of message delivery has to be guaranteed. Thus, in particular a low channel access time of the vehicle originally transmitting the message is a crucial requirement that has to be fulfilled in order to successfully apply the application. In this example, the third vehicle, initially being positioned 100 m away from the first vehicle needs to receive the information within 200 ms or less in order to successfully avoid a collision in this particular situation. Translated to the communication requirements that we apply in the simulation studies in Chapter 6.5.3, we would have to cover an awareness range of 100 m with 100 % reliability, and an additional constraint of a channel access time lower than 200 ms has to be fulfilled. Yet, 100 % reception reliability can never be guaranteed. Instead, multiple transmitted packets within the maximum delay of 200 ms, each having a lower reliability would alternatively also support the application. The multi-transmissions approach is e.g. presented in [Sepulcre & Gozalvez 2007].

2.3.2 Communication challenges

As can be seen from the safety application examples the major challenge of V2X communication is establishing reliable and timely information exchange under hard constraints inherently caused by the communication scenario. The following different constraints make communication challenging in particular.

Radio propagation: When radio signals propagate, their characteristics change over time and space. This change is often described by mathematical expressions, the radio propagation models. Radio propagation characteristics typically represent path loss, shadowing and fading behavior. The effects are caused by the physical environment in which the signals propagate. At the radio receivers the mentioned effects lead to interferences between different propagation paths of one transmitted signal. The analysis and modeling of these interferences and of their consequences on signal reception are a major subject of this thesis.

Distributed decentralized system: A V2X communication network consists of a huge number of vehicles equipped with communication technology and also possibly stationary road side units (RSUs) that participate in the communication. Such a communication system is inherently distributed and decentralized. In geographically limited systems (e.g. a WLAN access point (AP) that provides wireless access for a part of an office building) a centralized control is possible and the AP may provide management and coordination functionality. For V2X communication networks, in contrast, such centralized control is not applicable. Instead, an immediate and direct communication among all nodes in a specific environment has to be established, provided in a decentralized, yet coordinated manner. The aspect of decentralized control is a reason for imperfect coordination and leads to interferences of uncoordinated transmitters.

Broadcast communication characteristics: Data traffic from safety applications in V2X communication networks is mainly transmitted as broadcast traffic. Broadcast in this context means that the information transmitted is not addressed for one specific receiver node, but the content is of interest for every node positioned in the surrounding of the transmitter. The challenge of such message distribution is that a reception by every node within a specified surrounding cannot be guaranteed as there is no suitable way to acknowledge the reception of broadcast messages. Even if there would be acknowledgement schemes, it could still not be guaranteed that every possible receiver actually got the message due to the fact that there is no information on how many nodes are potential receivers. In consequence, reliability of transmissions in its classic way of understanding cannot be guaranteed for broadcast communication. This aspect makes the (negative) consequences of interference effects even more severe when broadcast transmissions are affected.

Mobility: Nodes in V2X communication scenarios have mobile characteristics. Each node typically has its own way of moving as each driver has an individual geographical location he wants to reach. Yet, the degree of freedom is limited by the road network, by traffic rules and restrictions and by the behavior of other vehicles sharing the same road. Nevertheless, it is difficult to predict the movement of an individual vehicle and it is also not trivial to precisely characterize the traffic situation and its evolution in general. The mobility of the nodes affects communication, as radio characteristics continuously change and the network topology varies.

2.4 Standardization activities

Different initiatives worldwide focus on the standardization of V2X communication networks. It is obvious that inter-operability of systems from different original equipment manufacturers (OEMs) and from other manufacturers can only be achieved by commonly known and widely accepted architectures, protocols and definitions. Clearly, there is a trade-off with respect to flexibility and with respect to the further development of according systems. As vehicles have a long life-time and market introduction of systems also takes long, there is the need for specifications that can be relied on for a long time, but that still allows future improvements and extensions.

In the following we will present the current activities with respect to overall system and station architecture as well as frequency allocation in the United States and in Europe. Then we will concentrate on the lower communication layers, in particular IEEE 802.11p.

2.4.1 Architectures

A wireless communication system consists of entities that communicate with each other. Each entity is at a specific position at any point in time. The communication is enabled by the exchange of messages over the air, the wireless medium. Each communication entity is part of a more complex systems like a computer, notebook or an embedded device. We concentrate on the pieces of the system that are relevant for the communication.

A communication system is structured in different components that have defined dependencies and interfaces between each other. The typical model is organized in a stacked structure, thus, a stack of functional components where information is exchanged between components on neighbored layers. Each layer provides services to higher layers while making use of the services of components on lower layers. The interfaces are defined as service access points (SAPs).

Components in different communication entities but on the same layer can establish a communication connection. It is important to distinguish between logical and physical connections: logical connections use the services provided by lower layers to exchange the data, thus, the connection needs the support of other systems, and both entities have to “speak the same language”, i.e. follow the specifications of a communication protocol. On the lowest layer a physical connection between the communication entities exists only by electromagnetic waves that are exchanged between the entities. Thus, we state that the entities are connected via a “real” wireless communication channel.

If we want to characterize the communication between two entities we have to specify the layer that we consider. This work concentrates on the lower communication layers, i.e. medium access layer, physical layer and the wireless physical transmission. In the following we give a short system overview and characterization.

One important aspect with respect to a broad acceptance of V2X communication systems are low costs for system development, introduction and maintenance. Thus, the adaption of established and relatively cheaply available hardware components and known software architectures is a straight forward strategy. Yet, even established systems have to be adapted to the specific deployment scenario. The currently followed way is the adaption of technologies in the wireless local area network (WLAN) domain for use in V2X communication networks.

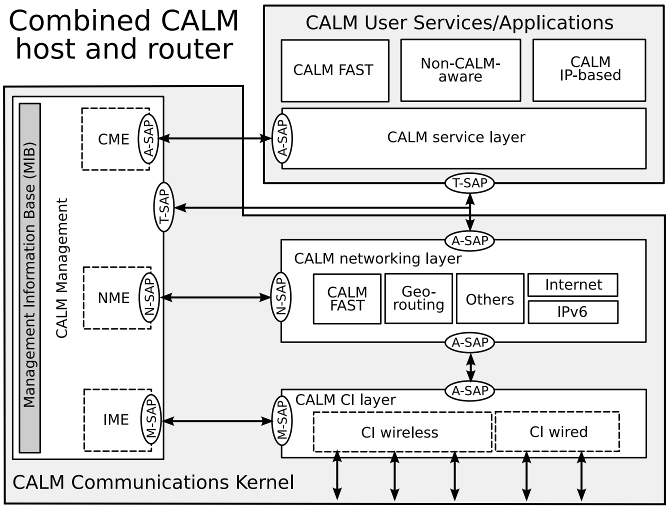

Figure 2.2: CALM station architecture (adapted from [COMeSafety Project 2008])

Over the time, several architectural frameworks were developed and presented. A basis for many frameworks builds the architecture developed by the ISO TC204 WG16, the CALM architecture [WWW CALM]. CALM stands for "continuous air interface for long and medium distance", thus, the working group defines an ITS architecture for the field of V2X communication. The CALM architecture does not define one specific communication technology, but allows multiple possibilities. Figure 2.2 shows the architecture of a station in the continuous air interface for long and medium distance (CALM) architecture, either in the infrastructure or on a vehicle. As can be seen, the architecture is divided into different layers: user services and applications on top, the networking layer in the middle and the communication interface (CI) layer on the bottom. The layers are connected by well defined interfaces, the SAPs. Each of the layers includes several possible applications, protocols or communication technologies. The management plane is organized orthogonal to the three layers and allows the configuration and management of the whole unit.

The standardization efforts in the United States also build upon an layered architecture: the wireless access in vehicular environments (WAVE) protocol stack that is defined by the Institute of Electrical and Electronics Engineers (IEEE) 1609

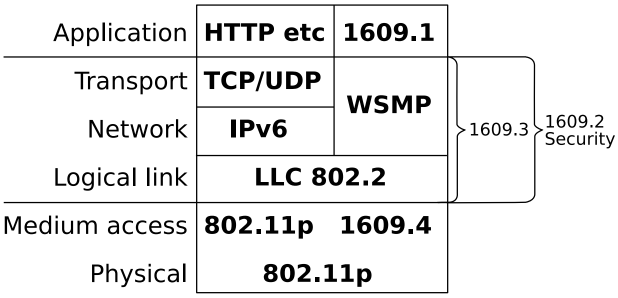

Figure 2.3: WAVE architecture

working group [WWW IEEE 1609] and is shown in Figure 2.3. It consists of two separated communication stacks for the higher communication layers, depending on the application that should be performed. While infotainment applications use the Internet protocol stack that uses TCP or UDP as transport protocols and IPv6, traffic safety related communication uses a specific protocol stack, the WAVE short message protocol (WSMP). The according protocols and mechanisms are part of the IEEE 1609 standards. The lower layers are specified in the IEEE 802.11p draft standard.

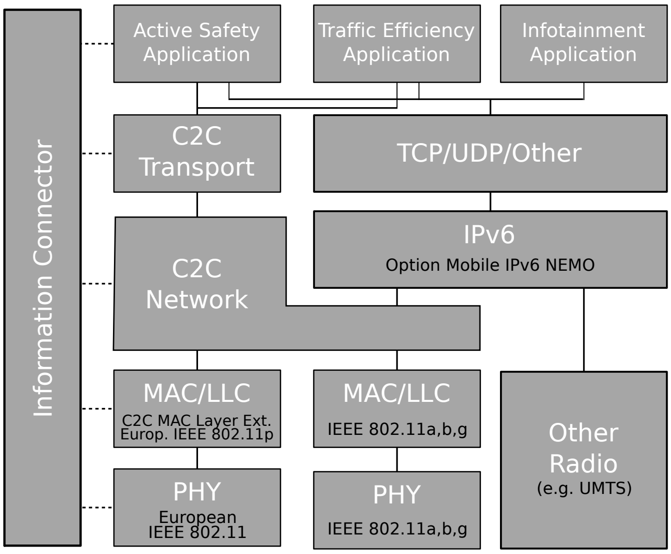

Figure 2.4: C2C communication layer station architecture (adapted from [WWW C2C-CC Manifesto])

The C2C communication system shown in Figure 2.4 was proposed by the C2C-CC for use in Europe and has some relations to the WAVE communication stack presented before. On physical layer (PHY) and medium access control layer (MAC) layer three different types of wireless technologies are distinguished: IEEE 802.11p adapted for usage in Europe, conventional IEEE 802.11

WLAN technologies, and other radio technologies like GPRS or UMTS, thus, cellular network technologies. While non-safety applications may use the classic transport control protocol (TCP)/Internet protocol (IP) protocol stack, safety application are built upon a C2C network stack. An additional cross-layer component is defined, the Information Connector.

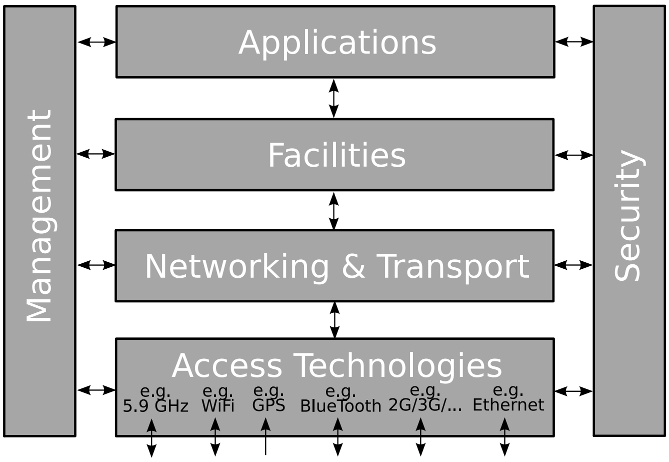

Figure 2.5: COMeSafety ITS Station Reference Architecture (adapted from [COMeSafety Project 2008])

Building upon the CALM and the C2C architecture, a unified ITS architecture for Europe was developed. The European ITS Station Reference Architecture is described in [COMeSafety Project 2008] and illustrated in Figure 2.5. Similarly to CALM, but also similarly to the C2C architecture, several communication layers are defined: applications layer on top, followed by a facilities layer and the networking and transport layer. Below, the access technologies layer is placed, where again multiple communication technologies may be used. Apart from the orthogonal management plane, the architecture also defines a layer-independent security plane. The major difference to the CALM architecture represents the facilities layer and the security plane. The facilities layer is capable to provide the basic services that are common for all applications and it bundles information that different applications want to transmit. As an example, positioning information is only contained once in the transmitted messages, but may be used by several applications. For direct communication between vehicles an adaption of IEEE 802.11p for use in Europe is defined, ETSI ITS G5A. In addition to the IEEE standard it contains mitigation techniques to avoid interferences with tolling systems and it adds transmit power control to the standard. The European Telecommunications Standards Institute (ETSI) is the central organization that coordinates the standardization efforts in Europe.

2.4.2 IEEE 802.11p

The overview on IEEE 802.11p provided in the following section is based on the corresponding section of our book chapter [Mittag et al. 2008] being published in [Hartenstein & Laberteaux 2010].

The first version of the IEEE 802.11 standard was published in 1997 and specifies the medium access control layer (MAC) and the physical layer (PHY) for wireless local area networks (WLANs). Over the years the standard was continuously developed and grew, so that numerous amendments were created in order to *i)* extend the functionality (e.g. in terms of security, quality of service, or interoperability), *ii)* support advanced transmission techniques and higher data rates (e.g. direct sequence spread spectrum (DSSS) or orthogonal frequency division multiplex (OFDM)) and *iii)* operate in several frequency bands (e.g. within the ISM bands at 2.4 GHz and 5.8 GHz). Several of these amendments were aggregated in one version to form the up-to date standard IEEE 802.11-2007 [802.11 2007]. The following paragraphs briefly describe the functional blocks defined in the standard, particularly focusing on the parts that have to be adapted for the operation in V2X communications.

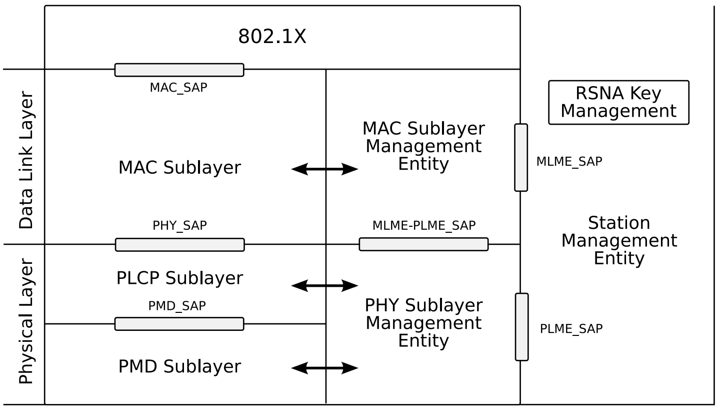

Figure 2.6: IEEE 802.11 reference model.

In Figure 2.6 the reference model of IEEE 802.11 is shown. Several functional blocks are specified that interact among each other over a set of service access points (SAPs). The left column contains the sublayers that establish wireless communication: the MAC sublayer includes the methods to access the medium in a coordinated fashion, the physical layer convergence protocol (PLCP) sublayer transforms the MAC frame into a medium-independent physical frame structure by adding preamble, headers and trailers and finally the physical layer medium dependent (PMD) layer encapsulates all functionality to transmit the data bits over the air and is individual for each transmission technology. Although the generic concept is the independence of higher layers from the characteristics of the physical transmission, both MAC and PLCP have some dependencies; exemplary, MAC parameters (slot times, inter frame spaces) are adapted depending on medium characteristics and application scenario, or, the PLCP frame format differs with the transmission technique used. The middle and right columns of Figure 2.6 illustrate the different management entities that are needed to manage and configure the different layers and the station as a whole. IEEE 802.11 has two external interfaces: one is the wireless interface, the other one is a SAP to the next higher protocol layer, logical link control (LLC), and provides the request of frame transmission to and signaling of frame reception from the wireless interface.

One of MAC and PHY's fundamental functionality is the definition of station addresses, the grouping of stations to connected sets and the addressing scheme in the exchanged frames. IEEE 802.11 offers different opportunities to build such so called basic service sets (BSSs). For instance, nodes can form a non-infrastructure environment independent basic service set (IBSS) with no central coordination authority, or, as in environments with infrastructure, i.e. an access point, be part of an IBSS which is identified by an individual identification number, the BSSID. An announced BSS may be joined by first scanning for available BSS, followed by an authentication and finally an association process.

IEEE 802.11 defines the frame structures at different layers. At MAC layer, a generic IEEE 802.11 MAC frame is defined that builds the basis for all existing frames. It includes a bit field for frame control, a duration field, several addresses, the frame body and a frame control sequence (FCS) for error detection. Within the frame control bit field the type and subtype of a frame is specified, so that specific frame formats for management, control and data transmission can be distinguished. Each subtype is derived from the generic format and adapted for the specified usage, i.e. specific fields and data elements are added or left out.

IEEE 802.11 provides several approaches for medium access control: point coordination function (PCF), that is only applicable if a central coordinating station like an access point is available, and distributed coordination function (DCF). Later, the standard was extended by more enhanced coordination functions that support the distinction of different service qualities, e.g. EDCA that will be explained in the next section. Here we first concentrate on DCF, as centralized approaches like PCF do not apply for V2X communication.

The DCF follows the principle of carrier-sense multiple access with collision avoidance (CSMA/CA), i.e. the channel is only accessed if the physical layer does not observe any ongoing activity on it and collision avoidance is provided by several additional technologies on the MAC layer described in the following. To allow medium access strategies the physical layer has to notify the channel status to the MAC layer, called clear channel assessment (CCA). It is not specified

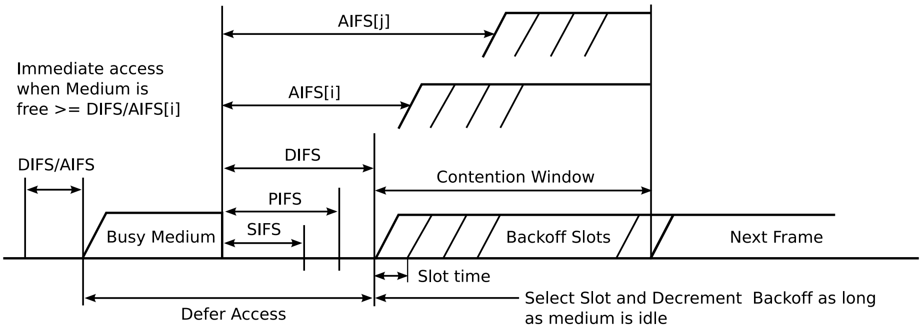

Figure 2.7: IEEE 802.11 distributed coordination function (DCF).

how exactly a wireless card should identify the status of the medium, instead, the medium should be indicated busy if the received power level is higher than a certain threshold in case a valid frame transmission is observed. It should also be indicated busy in the absence of a valid transmission if the received power level exceeds a second, higher threshold. An important mechanism is the inter frame space (IFS), time durations the medium has to be indicated as idle before the station may transmit. IFS of different length for different frame types allow a prioritized access. Exemplary, important control packets like acknowledgments are sent after a short inter frame space (SIFS), whereas regular data packets are not transmitted before the medium was sensed idle for the duration of a distributed coordination function inter frame space (DIFS), that exceeds the length of SIFS by two so called slot times. In case the medium is determined busy, Figure 2.7 illustrates the medium access strategy: the station selects a random number of backoff slots within a certain range, the contention window. The slots are counted down after the medium was sensed idle for the duration of a DIFS; the count-down is interrupted whenever the medium is determined busy. Whenever the count-down reaches zero the frame is transmitted. In case there is a unicast packets for which no acknowledgment is received, a retransmission is scheduled after a newly selected number of backoff slots under the use of an increased contention window (exponential backoff). Retransmission limits are defined that restrict the number of retransmission tries.

Several physical layer specifications exist in IEEE 802.11, here we focus on the amendment IEEE 802.11a that serves as the basic technology used for V2X communication. The adaptations specifically necessary for V2X communication are to be defined in the amendment IEEE 802.11p [802.11p 2009]. IEEE 802.11a operates in the 5.2—5.8 GHz frequency band and uses orthogonal frequency division multiplex (OFDM) as transmission technology. The channel bandwidth is therefore separated into 52 orthogonal sub-carriers, i.e. sub-carrier spacing is designed so that at the center frequency of one sub-carrier all others have an amplitude of

0. By using coding schemes, data bits are redundantly spread over 48 of these sub-carriers so that erroneously transmitted bits in one sub-carriers do not necessarily avoid a successful frame reception. Depending on the modulation scheme each sub-carrier encodes a specific number of bits in each symbol; exemplary, using the relatively simple binary phase shift keying (BPSK) modulation scheme, each sub-carrier encodes 1 bit. By applying an inverse fast Fourier transform (IFFT) the signals of all sub-carriers are transformed into the time domain as symbols of fixed length. Subsequent symbols are separated by a guard interval of fixed duration in order to avoid interferences between the distinct symbols (inter-symbol interference (ISI)). At a receiver the processing is applied in reversed order; of course, the IFFT is replaced by a fast Fourier transform (FFT). As OFDM is a transmission technology that gives higher robustness against changing and varying channel conditions compared to other spread spectrum approaches it is a reasonable choice for V2X communications. Despite the complexity of the OFDM transceiver hardware which is increased due to the necessary Fourier transform, this is not a critical issue anymore due to decreasing chipset prizes.

IEEE 802.11p is a variant of IEEE 802.11a that additionally covers the specifics of V2X: highly dynamic and mobile environment, messages transmission in an ad-hoc manner, low latency, and operation in a reserved frequency range. These specifics require several adaptations to the standard. Historically, the IEEE 802.11p standard evolved out of the "ASTM E2213-03 Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems" [ASTM 2003] that was transformed into an IEEE compliant style in 2004. In the following years standardization discussion continued, and the first version that successfully passed the IEEE 802 working group letter ballot was draft version 4.0. Currently (December 2009), the current draft version 9.0 of IEEE 802.11p passed the IEEE 802 working group sponsor ballot for the first time and is now again in comment resolution phase. Thus, IEEE 802.11p still is within the standardization process and further prepared in order to being approved and published. Though relating to an earlier status of the IEEE 802.11p draft, a further description of IEEE 802.11p development and design decisions is given by [Jiang et al. 2008].

Physical Layer

On physical layer IEEE 802.11p is similar to IEEE 802.11a, with some adaptations for the specific application domain. The operation takes place in a separate and reserved frequency band. In the United States the Federal Communications Commission (FCC) has allocated a 75 MHz wide frequency spectrum from 5.85 to 5.925 GHz in 1999. In Europe, a 30 MHz wide frequency spectrum was allocated by the Electronic Communications Committee (ECC) in March 2008, with a possible extension to 50 MHz. IEEE 802.11a specifies operation for 5, 10 and 20 MHz channels; while "classic" wireless networks typically use 20 MHz channels, 10 MHz channels are envisioned for V2X networks due to robustness issues and the possibility to re-use existing wireless chipsets. Several measurements, [Alexander et al. 2007; Cheng et al. 2007, 2008b], showed a Doppler spread (caused by the fast moving nodes) up to 2 kHz and RMS delay spread (caused by multi-path propagation) of up to 0.8 µs. In a 20 MHz channel of IEEE 802.11a the guard interval between subsequent symbols has a length of 0.8 µs and thus is critical being too short to mitigate ISI. A longer guard interval of 1.6 µs is achieved when using half the bandwidth, as it is done in IEEE 802.11p. The duration of a data symbol also doubles to 6.4 µs. Thus, the measured delay spread is shorter than the guard interval, mitigating ISI. Inter-carrier interferences ICIs are mitigated as well as the Doppler spread is much smaller than half the sub-carrier separation distance of 156.25 kHz. By only using half the bandwidth the capacity of the channel also reduces to the half, i.e. only 3 Mbps instead of 6 Mbps in the most basic mode. Due to multi-path propagation and the high vehicular mobility, the channel coherence time may be shorter than the duration of a data frame so that the channel estimation performed during preamble reception may become invalid at the end of a frame. Yet, solutions exist that overcome these limitations, e.g. by using an advanced receiver as proposed in [Alexander et al. 2007] in which a time-domain channel estimation and a frequency-domain channel tracking is performed to equalize the channel, or by using differential OFDM modulation proposed in [Zhang et al. 2008].

IEEE 802.11p specifies more adaptations that hardware devices have to fulfill, e.g. with respect to the operation temperature ranges and the allowed tolerances of frequencies and clocks. Low bit error rates support highly reliable communication, and IEEE 802.11p therefore (optionally) specifies more stringent regulations with respect to adjacent and nonadjacent channel rejection and transmit spectrum masks to reduce the influence of neighboring channels on each other.

Medium Access Layer

A fundamental difference of IEEE 802.11p compared to "normal" IEEE 802.11 networks is the ability to communicate outside the context of a basic service set to enable communication in an ad-hoc manner in a highly mobile network. The IEEE 802.11 authentication and association processes preceding a first frame exchange would last too long, e.g. in the situation of communication between two vehicles with opposing driving direction. Consequently, authentication and association are not provided by the IEEE 802.11p PHY/MAC, but have to be supported by the station management entity (SME) or a higher layer protocol. In the V2X use case the protocols of the IEEE 1609 standard family contain according procedures. IEEE 802.11p adds the mode of communication outside a BSS into the standard as this way of operation was not foreseen before.

The communication outside of a BSS reduces the functionality of MAC to the basic needs. All unnecessary frame formats are removed and only a small amount of necessary frames remains: data is transmitted using the *quality of service (QoS) Data* frame format to allow prioritization of frames on a packet level basis according to the enhanced distributed channel access (EDCA) mechanisms described in the next paragraph. Unicast frames are acknowledged and may be preceded by an optional request to send (RTS)/clear to send (CTS) frame exchange. A special management frame is introduced, the *Timing Advertisement*. It is suggested to allow roadside units to advertise information on the services provided in a fast fashion. Such information may contain timestamp and time synchronization information, supported data transmission rates or information on enhanced station coordination (EDCA), and the possibility to announce services of higher layers as e.g. specified in IEEE 1609.

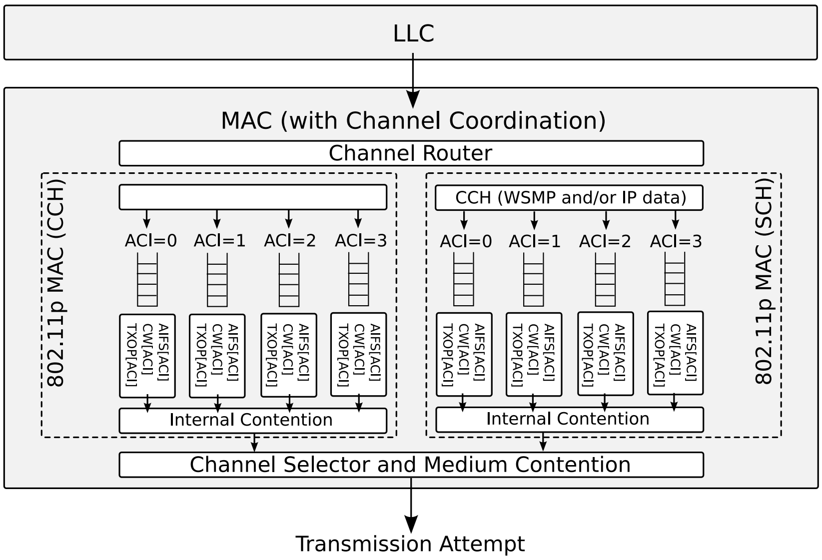

Figure 2.8: IEEE 802.11p enhanced distributed channel access (EDCA).

An important aspect for vehicular communications concerning safety will be the prioritization of important safety- and time-critical messages over the ones that do not directly concern safety. IEEE 802.11p therefore specifically adapts enhanced distributed channel access (EDCA) that was originally proposed in the IEEE 802.11e amendment of the standard, introducing quality of service (QoS) support. The medium access rules defined by the DCF are replaced by the ones of EDCA, where four different access categorys (ACs) are defined. Each frame is assigned one of the four access categories by the application creating the message,

Access Category Index	AIFSN	CW_{min}	CW_{max}
0	6	7	15
1	9	15	1023
2	3	3	7
3	2	3	7

Table 2.1: WAVE EDCA parameter set for the operation outside of a BSS

depending on importance and urgency of its content. Each AC is identified by its access category index (ACI), holds its own frame queue and has an individual set of parameters coordinating the medium access. Figure 2.8 gives an overview of the EDCA architecture in V2X communications: two types of supported channels are shown, the common control channel (CCH) and the service channel (SCH) as described Section 2.4.3. For each channel four separate queues are provided, each of them having a specific setting of contention parameters, shown in Table 2.1. The arbitration inter frame space number (AIFSN) replaces the fixed DIFS time defined in the DCF. The time the medium has to be sensed idle before it can be accessed has to exceed the time of a SIFS by AIFSN slot times. Also, the contention window minimum and maximum values are individual for each AC. Exemplary considering the values given in Table 2.1, frames sent with ACI=3 have high chance to access the medium earlier due to the lower AIFSN value and the lower contention window borders in case of a backoff. Summarized, frames with an ACI of 0 have regular access, an ACI of 1 is foreseen for non-prior background traffic, while an ACI of 2 and 3 is reserved for prioritized messages, e.g. critical safety warnings. Yet, there is no strict prioritization: contention between the access categories is resolved internally; only the frame having the lowest waiting time actually contends with other stations on the medium. Note that “internal” collisions are possible; in this case the frame of the higher access category (having a lower ACI) is preferred.

2.4.3 IEEE 1609

The IEEE 1609 trial use standards [WWW IEEE 1609] provide the services on the layers above the ones defined by IEEE 802.11p. The IEEE 1609 drafts are currently again reviewed and newly structured. We will provide a very short overview on the most relevant parts of this standard when considering V2V communication. IEEE 1609.3 provides the networking services for V2X communication. A specific communication stack and a communication protocol is defined for use in vehicular networks, the WAVE short message protocol (WSMP). The definition allows the flexible composition of WSMP frames ranging from 16 byte up to over 2 000 byte but will typically have sizes of hundreds of bytes. In IEEE 1609.2 the additional security services for V2X communication are defined, including station authentication and message encryption. IEEE 1609.4 provides a specifications to support multi-channel operation. As it was shown up to seven channel are defined and defined procedures have to be followed to make use of multiple channels. IEEE 1609.4 is related to the EDCA mechanisms already described.

For our work, the IEEE 1609 standards provide the order of magnitude which can be expected for typical packet sizes. In Chapter 6 we will vary several configuration parameters, among them the packet size, over relevant ranges in order to achieve a performance evaluation within realistic ranges.

2.5 Summary and focus of this thesis

In this chapter, we achieved an overview of the field of V2X communications. We briefly reviewed research projects and the use cases for which V2X communication can be applied. Further, we showed for an exemplary application that communication could provide advancements with respect to traffic safety and we derived the communication requirements that are necessary, Then, we assessed current standardization activities, showed envisioned architectures and especially explained the details of the IEEE 802.11p draft proposal.

In the subsequent chapters of this thesis we perform several steps to finally be able to do a broad performance evaluation of vehicular communication systems that base on the IEEE 802.11p technology. The applications, systems and standards presented in this chapter provide the necessary base system that we refer to during modeling and simulation phase. The goal of this thesis is on the one hand to provide methodologies and to be capable to achieve system performance measures before according systems can be tested in reality in very large scale. Thus, the results obtained allow to predict how systems will perform in future.

3

Background and related work

In this section we will take a look on related work with respect to the characterization of radio wave propagation and to radio channel models, as well as the discussion of interference and its mitigation. Radio propagation and interferences are the major aspects that underlie most of the challenges that occur in wireless communication networks, thus, it is essential to be aware of the phenomena that take place.

3.1 Radio propagation

In this section we will present methods to describe and characterize radio wave propagation. Radio wave propagation forms the basis for wireless communication and follows the underlying physical principles, thus, the laws that are apparent to electromagnetic waves. The underlying fundamental physics theory is formed by the Maxwell equations that describe the field characteristics of electromagnetic waves. Here, we want to consider the topic from a less abstract perspective, related to the needs of wireless communication.

We will first give the basic concepts of wireless communication, and will then describe the important characteristics. We will then present models that represent different effects affecting radio propagation, then consider modeling approaches for the V2V communication channel and finally investigate efforts of empirical measurements.

First we consider direct communication between two entities, one transmitter and one receiver. The next Section 3.2 will then elaborate the influence of multiple transmitters. The model of a *communication channel* is commonly taken for the description and characterization. The channel represents a resource that is used to establish a connection between two communication entities, a transmitter of information and a receiver of this information. In [Gallager 2008, p. 8] the following description is given: "In general, a channel is viewed as that part of the communication system between source and destination that is given and not under the control of the designer." The description states the inherent challenge with respect to communication channels: while the other pieces of a communication system can be designed, optimized and controlled, the channel is naturally given and can only be used. In order to efficiently using it a channel characterization is necessary. [Matolak 2008] states that "one can define the channel as the complete set of parameters for all paths that transmitted electromagnetic waves in the frequency band of interest take from transmitter to receiver over the spatial region of interest". Consequently, *channel models* describe the characteristics of the communication channel. Such models vary in the level of abstraction and cover different levels of detail, i.e. the models may respect or ignore physical effects that could influence the communication characteristics. As [Matolak 2008] further states, the "characterization must be quantitative and as thorough as possible. Conversely, the thorough description must not be so complex as to limit its usefulness; thus a balance is sought."

3.1.1 Physical channel characterization

An often taken approach to characterize wireless channels is the description of its characteristics as a statistical model. On the intent of a statistical model [Gallager 2008, p. 8] states: "A channel is usually viewed in terms of its possible inputs, its possible outputs, and a description how the input affects the output. This description is usually probabilistic."

A wireless channel can be characterized from the view of physical phenomena occurring to electromagnetic waves. Signals on the channel are mainly influenced by three basic phenomena. Reflection occurs, when a wave hits an object of very large dimension compared to the wavelength of the wave. These objects can be, e.g., buildings, walls or the ground. If a wave is reflected, it changes its direction and may change its phase, too. Diffraction occurs if a wave hits an object that has sharp irregularities like edges. Is this the case, the wave is not reflected in one direction, but many secondary waves occur, that continue propagating and have different amplitudes and phases each. Scattering occurs if the medium the waves propagate through contains a high number of objects that are small compared to the wavelength, e.g. lamp posts or street signs. These effects split one wave that is sent into several ones. At a receiver several of these waves arrive and they interfere with each other. This effect is called multi-path fading.

Three types of models are used to describe the effects on the signal, these are i) large-scale path loss, ii) shadowing or large-scale fading and, iii) small-scale fading. We will give brief explanations of the different phenomena in the following, see e.g. [Rappaport 2002] for more details.

Large-scale path loss relates to the physical phenomenon of wave radiation in the far field, i.e. the field many wavelengths away from the antenna (as wavelengths in the vehicular domain are in the magnitude of several centimeters, all relevant communication distances are in the far field). The energy that is radiated by the antenna is distributed over a sphere of increasing size around the antenna. The area of this sphere is increasing with d^2, where d is the distance from the antenna. Accordingly, if a lossless distribution of transmitted energy is assumed (so called free space propagation) the power of the signal in distance d decreases with d^2. Higher coefficients in power loss respects the obstruction of free space propagation, more details are discussed in Section 3.1.2

Shadowing, or large-scale fading, is a physical phenomenon that occurs whenever the radio waves have to pass solid material, e.g. walls, that absorb some of the energy. The characteristic of this type of influence lies in its long presence, on the order of seconds or minutes. For our considerations in V2V networks, shadowing effects may occur when the waves have to pass vehicles like trucks, and it is of interest when considering urban scenarios, e.g. at intersections. Nevertheless, due to the mobility and dynamics of V2V networks, shadowing conditions may quickly vary over time and there is some difficulty in precisely reflecting the individual situation and corresponding shadowing effects.

Small-scale fading, or simply fading, relates to the phenomena described in Section 3.1.3. The effect describes fast changes and variations (fades) of reception conditions due to changes in the environment, or due to a moving transmitter or receiver. These fast changes in the received signal lead to challenging conditions at the receiver unit, as the signal should be decoded successfully despite the rapidly changing conditions.

From the explanations above, an often chosen way of describing the reception characteristics of a signal lies in subsequently applying mathematical descriptions of the three described phenomena to the transmitted signal: first, the signal attenuation due to the path loss is calculated, then, shadowing effects are additionally considered, and finally, the effects of fading are applied. In the following we will take a closer look on large-scale path loss and on small-scale fading as these two physical phenomena are the major modeling within this thesis. Shadowing is omitted due to the fact that we in this thesis concentrate on outdoor communication on highways, thus, buildings and concrete walls are not considered, and we neglect the detailed representation of large vehicles in our considerations.

3.1.2 Large-scale path loss

Large-scale path loss models describe the average received signal strength that can be achieved at a receiver in a specific distance from the transmitter of a signal, thus, the large-scale path loss model describes the general slope of signal power over distance.

Deterministic radio wave models assume that the received power at a certain distance is always the same under identical conditions. These models consider the physical effects described only in a general way. When using the Free Space or Friis model, it is assumed that electromagnetic waves propagate ideally without influence of the environment, see [Rappaport 2002, p. 107]. As described before, the received power P_r decreases with the square of the distance between sender and receiver: $P_r \sim \frac{1}{d^2}$. The model predicts the received power at a certain distance d under ideal conditions as

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

where G_t and G_r represent factors that take into account the quality of the antenna used (the antenna gain), λ is the wavelength on which the communication takes place and L is a system loss factor that is chosen as 1 in an ideal environment. P_t represents the transmission power.

When considering two paths, the direct path as well as a path that is reflected on the ground, the Two Ray Ground model is used. The length of the reflected path is longer than the direct one, and consequently waves transmitted over the reflected path arrive later at the receiver. According to [Rappaport 2002, p. 124] the average received power when considering the Two Ray Ground model is

$$P_r(d) = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \tag{3.2}$$

where $P_r(d)$ is the received signal power, that depends on the distance d between transmitter and receiver, P_t is the transmission power, G_t and G_r the antenna gains and h_t and h_r the heights of the two antennas beyond ground. As one can see from the equation the received power decreases with the distance to the power of four what induces a stronger decrease than predicted in the Free Space model.

Under the Two Ray Ground model, the Fresnel distance gives the distance where the received power predicted by the Two Ray Ground model equals to that predicted by the Free Space model. If the distance between sender and receiver is higher than the Fresnel distance, the two-ray ground model is used, otherwise, the Free Space model. The Fresnel distance is calculated by

$$d = \frac{4\pi h_r h_t}{\lambda} \tag{3.3}$$

where h_r and h_t are the antenna heights of the transmitting and receiving node and λ is the wavelength of the transmission.

There exist more advanced models for large-scale path loss description, see for example [Rappaport 2002, ch. 4]. Yet, later for our simulation considerations we make use of large-scale path loss with respect to a deterministic model. The achieved average value is then further processed by a small-scale fading model such that variations signal reception power do occur. Measurements show that this general approach of combining a deterministic path loss with probabilistic small scale fading leads to represents achieved reception values considerably well, see e.g. [Taliwal et al. 2004].

3.1.3 Small-scale fading

The fading behavior of a signal can be described by considering the different paths over which the wave propagates. All objects in the environment influence the propagation of a wave, either by reflecting, scattering or absorbing it. Due to the typically available multitude of such subjects, a wave reaches the receiver by traversing different propagation paths. Each path has its individual characteristics (like signal attenuation) and its individual distance from transmitter to receiver, and consequently a specific propagation delay. For the discussions in the following only significant paths of the so-called *multi path environment* are taken into consideration, i.e. insignificant, highly attenuated paths are omitted. If there is a path that directly connects the transmitter and the receiver antenna this path is called the line of sight (LOS) path. The presence of a LOS component plays an important role in the later channel models.

In communications engineering a communication channel at one specific frequency is often characterized by its time-varying channel impulse response $h(t, \tau)$, that is, the response of a channel at time t due to an impulse input at time $t - \tau$. Such characteristics can be measured by so called power delay profiles that identify the variation of the channel over time t and the intensity of the different propagation paths with varying delay times τ. The received signal constitutes of the addition of propagation paths reaching the receiver at the same point in time, and an additional thermal noise component.

The characterization of a channel by its impulse response allows to further extract several important characteristics. The *delay spread* is defined as the difference between the path delay on the longest significant path and that on the shortest significant path [Gallager 2008, p. 348]. Often the root mean square value is used to express delay spread. The delay spread is of particular interest if its length is in the order of the duration of a digital symbol duration or longer (in digital communications, data typically is transmitted as symbols of specific length). Then, subsequent symbols may "mix up" with each other, thus, interfere with each other, see also Section 3.2.

The *coherence frequency* is closely related to the delay spread, it approximately lies in the order of the inverse value of the delay spread. The coherence frequency is a measure that expresses the width (in Hz) where the channel can be expected to behave similar over time, and at what frequencies a different behavior has to be expected. A communication channel that is wider than its coherence frequency is called a *frequency selective channel*. Frequency selectivity can both be advantageous and harmful, depending on the design of the communication system.

Another aspect of wireless communication channels relates to the consequences of non-stationary moving antennas. In that case, the frequency with which a radio wave is received is shifted in frequency compared to the one that was transmitted due to the movement of the antenna. Visually spoken, each crest of a transmitted sinusoid has to travel a slightly longer distance if the reception antenna moves away from the transmitter antenna; it travels a shorter distance if antennas move towards each other. The effect is known as the *Doppler shift* and is dependent on the relative speed of both antennas to each other. Thus, in a multi path environment every path changes over time due to the movement, and every path is affected by the Doppler shift. Conceptually similar to the delay spread, the *Doppler spread* is defined as the difference between largest and the smallest of the occurring Doppler shifts. As Doppler shifts depend on the carrier frequency of the transmissions, the Doppler spread is frequency dependent as well. The Doppler spread describes the width on which a transmitted frequency is spread when it is received.

The *coherence time* is closely related to the Doppler spread, it approximately is its inverse value. The coherence time of a channel describes the duration between two fades, thus, the time over which a channel can be assumed not to strongly change its characteristics. If the symbols that are transmitted over a channel are longer than the coherence time, the channel is called a *time selective channel* or, a *fast fading channel*.

The statistical channel model that can be derived from above mentioned considerations is called the *tapped delay line model*: the delay times of the different paths are binned into different taps. Each input signal to the model is processed over a delay chain and subsequently put into the different taps. Each tap has its individual attenuation characteristics, and at each time, the output signal is the sum of the output of all taps. Each individual tap may be described by a statistical distribution function. A detailed descriptions of according models can be found in [Gallager 2008, ch. 9] and [Rappaport 2002, ch. 5]. The specific application to V2V channels will be further discussed in Section 3.1.4.

The V2V channel has its very specific characteristics. As [Matolak 2008] states the V2V channel is by nature different from cellular and many other radio channels: transmitters, receivers and reflectors are all mobile, antennas are mounted at relatively low heights, due to physical environment dynamics, the channel may be statistically non-stationary. The consequences are that tap amplitude distributions change over time and space and that reflectors and scatterers may appear and disappear. With respect to the type of models [Matolak 2008] further states "Statistical models are often more attractive in that they do not attempt to provide exact estimation of a channel's small scale fading characteristics at points in space at any particular time; rather, they attempt to faithfully emulate the variation in these channel effects".

For our considerations we principally apply the strategy that Matolak proposes, we use statistical models to represent small-scale fading, thus, fading is represented by a probability density and concrete reception values are achieved by drawing values from an accordingly distributed random variable. We concentrate on the Rayleigh and on the Nakagami-m fading models. While the Rayleigh model is widely used to represent adverse channel conditions without a line of sight component and thus severe fading, the Nakagami-m model can be configured by its m-parameter to represent different intensities of fading.

Under the Rayleigh fading model the signal amplitudes are distributed according to a Rayleigh distribution that is given

$$g_R(x; \Omega) = \frac{2x}{\Omega} e^{-\frac{x^2}{\Omega}} \tag{3.4}$$

where Ω is the expected value of received signal strength [Simon & Alouini 2000, p. 20]. The signal to noise ratio (SNR) per symbol is then distributed according to an exponential distribution:

$$f_R(x; \Omega) = \frac{1}{\Omega} e^{-\frac{x}{\Omega}} \tag{3.5}$$

The Nakagami-m probability density function (pdf) [Nakagami 1960] describes the distribution of signal amplitudes and is given by

$$g_N(x; m, \Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} x^{2m-1} e^{-\frac{mx^2}{\Omega}} \tag{3.6}$$

where m is the Nakagami-m fading parameter ranging from 0.5 to ∞ and Ω is the expected value of received signal strength. Derived from the Nakagami-m distribution, the SNR per symbol is distributed according to a Gamma distribution [Simon & Alouini 2000, p. 22]. The Gamma distribution is generally given by

$$h(x; b, p) = \frac{b^p}{\Gamma(p)} x^{p-1} e^{-bx}. \tag{3.7}$$

By setting $p := m$ and $b := \frac{m}{\Omega}$ we derive the pdf $f(x; m, \Omega)$ that describes the distribution of received signal strength for an average received reception power Ω and the fading parameter m:

$$f(x; m, \Omega) = \frac{m^m}{\Gamma(m)\Omega^m} x^{m-1} e^{-\frac{mx}{\Omega}} \tag{3.8}$$

The parameter m allows to model signal strongly varying fading conditions from moderate fading (high m values), over Rayleigh fading ($m = 1.0$) to severe fading ($m = 0.5$). As discussed in the next Section 3.1.4, several measurement studies show that the Nakagami-m model is an appropriate fading model to well represent the channel conditions in vehicular communication networks.

3.1.4 Empirical measurements of vehicle-to-vehicle communication channels

This section will give an overview of measurement campaigns to derive the channel characteristics in vehicular networks. The measurements provide the fundamental information that is necessary to derive models that describe the communication channel appropriately.

In [Acosta-Marum & Ingram 2007] measurements in the 5.9 GHz frequency band were done for six different environments in urban, suburban and rural environment situations with measurement equipment. The measurements were applied to achieve a small-scale fading model of the according channels. The results contain all important characteristics for the six scenarios and for up to eight time taps, like path loss, delay, frequency shift or Doppler analysis. The extracted information is used to be injected into a channel emulator. With the emulator, tests were performed with test equipment that follows the definitions given in the proposed Standard IEEE 802.11p (see Section 2.4.2). The study shows that the V2V channel clearly is time-selective and frequency-selective.

The study presented in [Cheng et al. 2007] was done in the 5.9 GHz band as well, and the radio transmissions between two vehicles driving in a suburban area were measured. A narrow-band signal at the frequency of interest was generated by a digital signal generator, and a signal analyzer was used to identify characteristics of the wireless channel. The study identifies configuration values for the path loss modeling as well as parameters with respect to characterize small-scale fading. The path loss model shows good match to a dual-slope model with coefficients 2 and 4. The small-scale fading characteristics underline a modeling of small-scale fading by the Nakagami-m distribution, with varying parameters from 4.0 to 0.3 for different distances between transmitter and receiver. Further studies of the same team [Cheng et al. 2008b, c, a] provide additional details.

In [Taliwal et al. 2004] a measurement study is briefly described in order to achieve model parameters for V2V communication on a highway. The study derives a dual slope path loss as well, with coefficients 2 and 4 and a crossover distance of 160 m. The Nakagami-m fading parameter varies between 4.0 and 0.5. Unfortunately, the study does not give details on the approach with which data was measured.

The publications [Matolak et al. 2006] and [Matolak 2008] also identify V2V communication characteristics. Apart from measurements, the particular effects of the rapidly changing paths are brought into the modeling of the channel by applying a Markov model to activate and deactivate the influence of specific taps in a statistical way. Thus, from measurements, the probabilities that a specific tap influences the received signal is identified, and the corresponding values used for an according On/Off process.

There are also large measurement campaigns like Wireless World Initiative New Radio (WINNER) [WINNER 2007] that perform the characterization of the wireless channel under varying environments and that provide according models to be used in further studies of the systems.

In [Alexander et al. 2007], measurements are discussed that compare the indoor and vehicular outdoor usage of IEEE 802.11 approaches. It is shown that the multi path characteristics of outdoor and mobile application lead to strongly reduced performance of the communication performance. The work indicates the necessity of advanced receiver architectures that allow to significantly improve outdoor performance of IEEE 802.11.

The different measurement campaigns provide a first insight on the expected radio capabilities of vehicular communication. Due to the varying environments, setups and scenarios, however, a clear and complete characterization of the communication channel is still an issue under investigation.

3.2 Interference

In this section we discuss the situation that there is more than one single distinct transmission between one transmitter and one receiver going on. Instead of reviewing the characteristics of a single transmission we now consider multiple transmissions in a network, taking into account that in this thesis we look at geographically local broadcast transmissions. In principle, we now transfer from a communication to a networking point of view and consider mutual interference.

The Encyclopaedia Britannica defines *interference* as follows:

> *"In physics, the net effect of the combination of two or more wave trains moving on intersecting or coincident paths. The effect is that of the addition of the amplitudes of the individual waves at each point affected by more than one wave."*
> according to [WWW Encyclopaedia Britannica 2009].

In general, interference is not a priori a negative effect. In communication, however, the goal is the extraction of one originally transmitted wave form at a receiver, and consequently, interference has to be either explicitly used, e.g. as communication standards making use of multiple antennas (MIMO) do, like IEEE 802.11n, or alternatively, interference has to be mitigated as best as possible. IEEE 802.11p does not use multiple antenna approaches, and making use of interference mitigation is generally hardly possible when communication is based on broadcast transmissions.

We first present the general concepts before discussing how they are applied in IEEE 802.11p based communication or how they affect such communication. In principle, there are three different sources of interference. From the perspective of a receiving node interferences can be caused by transmissions on other communication channels (*multi-channel interference*), by the fact that transmissions follow multiple paths as explained in the last Section 3.1.3 (*multi-path interference*), or by multiple overlapping transmissions on the same channel (*multi-user interference*).

There exist four general approaches to mitigate interferences, thus, possibilities to keep signals distinguishable at a receiver. *Frequency division* separate transmissions on different channels that use distinct frequency ranges to transmit signals. *Space division* covers the possibility of separating signals by the location in which they are present. Either signal transmissions have to be directed and thus restricted with respect to their spatial distribution, or transmitters have to geographically separated such that they do influence each other at any relevant location. By *time division* the moments of transmissions on the channel are coordinated among the transmitting such that the signals do not overlap in time and thus can not interfere with each other. Finally, *code division* overlapping transmissions are possible, but a set of coding rules for the different transmission is used that allows their differentiation at a receiver. Each individual transmission is encoded following one individual code, and a receive is able to extract the relevant signal when the code that was used is known.

With respect to IEEE 802.11p, several design decisions are done and methods are used to mitigate interferences, or to respect their consequences. We concentrate on communication on the common control channel in the following (the service channel are not considered for the moment), thus, on messages that are transmitted on one channel.

With respect to interference mitigation during the access of the wireless channel we achieve the following: frequency division is not applied as a single CCH is used. Space division is applicable only partially. Nodes being geographically separated may make use of the channel in parallel. At near distances, yet, as broadcast transmission should be supported, a restriction of the direction of transmission is not possible and contradicts the intention of a broadcast. The use of code division is not applied by IEEE 802.11p in principle. For the application scenario considered it would be necessary that each transmitter has an individual code that is known by the receiver, what can only hardly be achieved. Further, code division afford the control of transmission power such that a similar power level from each transmitter is obtained by the receivers. Again, this contradicts the intention of communication usage in our scenario, as individual power control cannot be provided in parallel for all possible receivers. Time division is the scheme actually applied by using CSMA/CA as described in Section 2.4.2. We consider the scheme in the next paragraphs when describing multi-user interference.

Now we consider the sources of interference. Multi-channel interference should be mitigated by the definition of transmit spectrum masks in the standard document, see Annex I of [802.11p 2009]. A transmitter is restricted to not transmit energies higher than a specified level at frequencies that differ from the assigned center frequency. Several levels are defined with respect to the amount of deviation from the center frequency. Further, transmitters have to pass tests that assure that the reception of packets is still possible if transmission power on adjacent or non-adjacent channels occur, and the power does not exceed a specific power level. Multi-path interference causes the appearance of fading effects as described in Section 3.1.3. The transmission scheme of IEEE 802.11p, OFDM, allows receiver chipsets to be capable to handle some level of multi-path fading. Multi-path fading may further lead to delays that exceed the borders of a packet and thus cause interference with a subsequent symbol. Such inter-symbol interference (ISI) is mitigated by guard intervals defined in the standard, thus, time intervals that separate subsequent symbols. For IEEE 802.11p, guard intervals last 1.6 µs, thus, paths that vary in their length up to the time that waves propagate with speed of light during the guard interval time, thus 480 m, are still acceptable.

Multi-user interference is mitigated by the use of medium access schemes that are based on CSMA/CA. With such a scheme the channel may be accessed only if a node that wants to transmit a message does not sense any other transmission on the channel, see Section 2.4.2 for details on the DCF and EDCA schemes. The use of a random number of backoff slots reduces the probability that two transmitters that are geographically near to each other access the channel at the same moment in time, yet, the procedure cannot avoid such parallel access. In our study, for broadcast transmission we in consequence use a higher contention window such that the probability of parallel access due to the same choice of slots is reduced. Yet, there is the effect of hidden nodes that access the channel during the transmission of another packet and thus cause multi-user interference. The CSMA/CA procedure decides on whether the channel is in use or not by measuring the signal power on the wireless channel. Due to large-scale path loss, the received powers become low over distance. In consequence, a node may sense the channel idle and thus cause a transmission although there actually is another ongoing transmission that "only" has a low reception power at the specific receiver. The small-scale fading characteristics of the channel cause an amplification of hidden node effect as reception powers can considerably vary what may cause even more nodes to detect an idle channel although it actually is not. At a receiver node positioned between such two transmitters, however, multi-user interference occurs, leading to a collision of packets. The effect can be mitigated by techniques in the receiver that may successfully decode one of the messages if its reception power is stronger than the other one, also see Section 5.3.3. The capture capability of receiver chipsets is another technology to mitigate multi-user interferences, see Section 5.2.2. In this thesis the consequences of multi-user interference are a central part of the assessment provided in Section 6.

4

Definition of local broadcasts capacity

In this chapter, we theoretically analyze the fundamental communication pattern that arises in V2V networks. We consider periodic broadcasts by all vehicles that are transmitted with the intent that a mutual awareness is achieved among all vehicles that currently are in near local distance to each other. Each vehicle provides its own status information (like position, speed, acceleration, direction of driving, etc.) to the vehicles in its surrounding by periodically transmitting the according information to a communication channel that all vehicles commonly share, thus to a multiple-access broadcast channel. If all vehicles periodically provide their status information, and if the communication system could guarantee the successful reception of the status information messages at all vehicles within the awareness range, every vehicle would be capable to construct its local view on the current vehicular traffic situation, i.e. the current positions of all other vehicles within the awareness range. In this section we will analytically consider the bounds and feasibility of the communication system to provide the described local periodic broadcast service.

In principle, this chapter gives theoretical answers to basic questions: how reliable can multiple periodic broadcast messages be transmitted that are generated by all nodes in a scenario and that contain information being relevant at all nodes in an awareness range? What is the maximum capacity and data rate that a communication system can achieve when it is used as for local broadcasts communication? We develop a new definition, *local broadcasts capacity*, that, as can be derived from its name, takes into account the aspects of *i)* the geographically local relevance of the information ("local"), *ii)* the multitude of broadcast messages ("broadcasts") and, *iii)* the limited communication resource ("capacity").

Local broadcasts capacity relates to information theoretic problems that consider possibilities to efficiently make use of the channel provided. Although we will define the problem here, we will not be able to solve it in an information theoretic manner. The goal of this chapter is to define local broadcasts capacity and to analyze its characteristics. Finally, we want to be able to decide under which configurations V2V communication is able to provide the service that is required by applications, and in which not. We discuss the question what amount of broadcast traffic can actually be transmitted over a limited communication medium.

A communication channel makes use of a specific amount of available bandwidth in order to encode and transport information on the channel. A fundamental theorem from information theory, the *Shannon-Hartley theorem*, gives a relationship between bandwidth and its *capacity*. The channel capacity defines a theoretical upper bound on the amount of information per time that can be transmitted over a noisy communication channel with arbitrarily small error probability. More specifically, for communication over an additive white Gaussian noise (AWGN) communication channel, i.e. the transmission is disturbed only by thermal noise, the capacity c in [$\mathtt{bits/s}$] of a channel with limited bandwidth w in [Hz], a received signal power s in [W] and a noise power n in [W] is

$$c = w \cdot \log_2\left(1 + \frac{s}{n}\right) \tag{4.1}$$

As can be seen from Equation 4.1 the maximum capacity increases with broader bandwidth and it also increases with a better ratio of signal to noise power. The theorem further states, that for all data rates $b < c$, arbitrarily small error probabilities can be achieved by using an appropriate way of coding the data. It also states that for rates $b > c$ large error probabilities are to be expected. Yet, the law does not state what type of coding actually is appropriate.

Respecting the Shannon-Hartley law, communication systems can be designed, including the stated limitations. Designing systems is a trade-off between different objectives: *i)* closely reaching the theoretical limit, thus, efficiently making use of the provided bandwidth, *ii)* the effort that is needed to achieve the performance, and *iii)* the cost that has to be paid for development and hardware. Further, depending on how the communication system is organized and coordinated, its maximum capacity may vary a lot. Let us reconsider Equation 4.1: the available bandwidth w is fixed by regulation, see Section 2.4.2. The signal power at the receiver, s, depends on the maximum power that may be used for transmissions and also is subject to authoritative regulation. It mainly depends on the observed power attenuation on the wireless medium. The intensity of noise, n, is subject to even several influences. First, thermal noise and noise of the electronic parts are always observed. Second, external influences specific to the frequency range that is used for transmission can increase n. And third, the level of noise power can also be influenced by parallel transmissions from other communicating nodes, thus multi-user interferences, see Section 3.2. With respect to the signal under consideration, the reception power of transmissions from other nodes has to be considered as additional noise. In consequence, the ratio s/n at a receiver is of fundamental interest when considering the capacity of a wireless communication system.

In the following we want to concentrate on a communication system, that, from its design, is capable to transport a certain amount of information at maximum, thus, that has a maximum data rate of b, sometimes referred to as being the bandwidth of the system, although, as discussed before, bandwidth actually is the size of the frequency band that may be used. It is important to clearly distinguish these two issues. While bandwidth w and the Shannon law give a maximum achievable capacity c, the data rate b is the limit that actually bounds the capacity of an applied communication system. Thus, in order to consider how effective an actual system may be used, we in the rest of this chapter relate the capacity of a system b, the maximum achievable data rate of a concrete system. Instead of looking at one transmitter-receiver pair, we investigate the situation of many transmitters, each of them having multiple receivers that all share a single communication channel.

We first specify the scenario that will be analyzed in the following. We assume that there is one common channel available for V2V communication, as it is foreseen in current projects and standardization activities, see Chapter 3. In the sense of a communication system specific analysis, we assume that the system is capable to transmit data with a maximum data rate b expressed in [bits/s]. The achievable data rate depends on the technical realization of the communication system, thus, the data rate used here represents a limitation caused by the technologies that are used. The issue remains *where* the data rate b is measured and whether there are geographic dependencies. As we consider a distributed wireless communication system, the data rate may be used "in parallel" at locations widely separated. In nearby locations, however, the communication system requires a coordinated and synchronized use of the available data rate by the different transmitters in the system. In consequence, the data rate b reflects at each geographic location the maximum amount of data that all transmitters that have "influence" on the location may transmit together, given that they perfectly coordinate. The "influence" of a specific location raises the next question how such influence may be determined and described. For the analysis in the following we argue with fixed ranges of influence, the further considerations in this thesis, however, underly more realistic assumptions.

Yet, the definition of a maximum data rate yields some challenges. In case that one single node is transmitting data to another node the definition resembles the theoretical maximum amount of data that can be transmitted. In practice, the achieved bandwidth typically is lower due to the overhead of a transmission. Overhead can be caused by elements of the communication protocol that have to be added (e.g. preamble, frame control information), by additionally necessary control packets (in case of unicast transmissions e.g. frames for channel reservation (RTS/CTS), acknowledgement frames, or retransmitted frames), or by time intervals in which the channel may not be used, e.g. due to the medium access rules that have to be followed when the medium is shared.

The bandwidth definition causes further problems if broadcast transmissions are considered. In that case, using the bandwidth does not explicitly mean that the bandwidth is successfully used. Exemplary, at one receiver a successful reception might be possible, while, at another receiver, the reception fails. It is also possible that more traffic is generated than can be handled at some position. Consequently, in the process of this chapter a meaningful definition of bandwidth and available communication capacity in case that broadcast messages are exchanged is developed.

From an abstract point of view what we actually consider is a combination of several problems that have to be seen in combination:

- We have to handle a multiple receiver problem, i.e. a single transmission contains information for many receivers, and cannot be optimized to be best for a single receiver. The type of channel is known as broadcast channel, see e.g. [Xie & Kumar 2004].

- We have to handle a multiple sender problem, i.e. a single channel is shared by multiple transmitters, and they have to follow procedures not to interfere each other. The type of channel is known as multiple access channel, also see [Xie & Kumar 2004].

The combined result of both problems is a multiple access, multiple receivers channel. Figure 4.1 shows the different variants visually. The vertices represent nodes in the network, whereas the edges represent connections between transmitters and receivers. Edges with arrows are directional, while edges without arrows represent connections in both directions. Further, it has to be emphasized that

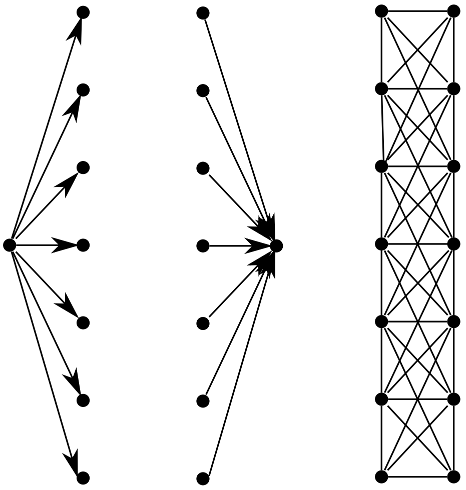

Figure 4.1: Sketch of different types of channels: broadcast channel, multiple access channel and multiple access broadcast channel. The arrows are not shown for the last channel as the connections are valid for both directions.

all the edges share one single channel, i.e. although in the drawing they appear to be independent and partially separated from each other, they are actually not. As can be seen, such type of model either assumes that communication is possible between two nodes, or not. This assumption clearly does not represent reality.

4.1 Related work

Before considering the multiple-access-multiple-receivers capacity problem that we will further discuss here, we review current literature and assess different publications with respect to capacity considerations. We observe that most work that was done with respect to capacity considerations follows a different goal and assesses different situations. Yet, we also observe some similarities to other approaches. In particular, a network view in contrast to a connection-oriented view is often not considered.

In information theory broadcast channels were first described and analyzed in [Cover 1972], and reviewed in [Cover 1998]. The publications discuss for different types of channels the problem of a single transmitter that simultaneously communicates information to several receivers. Without losing generality, the problem is reduced to the situation of a single transmitter and two independent receivers. It discusses how the rates achievable by the two receivers depend on each other, under the assumption of different channel models. The most similar model to our scenario is the Gaussian broadcast channels, where the signal of each link is independently disturbed by white Gaussian noise. The general outcome of the paper is that neither time-sharing (i.e. an individually adapted transmission to each receiver) nor adapting to the worst of all individual channels is an optimal strategy. The approach used by inter-vehicle communication with broadcast transmissions that cannot be optimized for any individual receiver cannot be represented by any of the extremes mentioned.

In [Gupta & Kumar 2000] the definition of capacity in wireless networks was introduced. In this work, capacity is defined as the achievable throughput per node that a network is capable transport. The work provided the basis for a whole field of research on the capability of wireless networks with respect to capacity. Yet, the work focused on unicast communication between pairs of nodes in the scenario and thus is not directly applicable to our case.

[Tavli 2006] defined a broadcast capacity for wireless networks and provided related boundaries: the per node capacity of a wireless network is bounded by $O(C/n)$ where C is the channel capacity in bits per second and n is the number of nodes. In the work, no spatial restriction of the broadcast is considered and the defined goal of broadcasting was to transmit the information to *all* other nodes in the network, if necessary by using multiple hops, what is not the intention in our work. A similar approach was taken by [Keshavarz-Haddad et al. 2006] and continued in [Keshavarz-Haddad & Riedi 2007].

[Li et al. 2004] derived analytic expressions for an optimal range so that 1-hop broadcast packets best cover a dense wireless network. Therefore assumptions with respect to the propagation of packet were made by defining a transmit circle and an interference torus around. The probability that an interfering node is positioned in a specific distance from the transmitter was derived and the number of affected nodes not receiving the original transmission estimated conservatively. The model of the radio channel was kept simple and represents a worst case analysis of failed packet receptions.

In [Goussevskaia et al. 2008] a problem similar to ours is discussed as an algorithmic problem and delivers asymptotic bounds of local broadcasting. The physical interference model is assumed. Interference is treated in two domains, from "close-in" and "far-away" nodes, i.e. the latter ones being nodes further away than a definable proximity range. The time is considered within which every of the nodes performs a successful local broadcast. Therefore, two different scheduling algorithms are presented, one under the assumption that the number of neighbors Δ_x^A in the proximity range A_x is known, and one where this number is not know. The algorithms allow a successful broadcast within poly-logarithmic time, i.e. after $O(\Delta_x^A \log n)$ resp. $O(\Delta_x^A \log^3 n)$ time slots. The paper provides asymptotic bounds, yet it mentions that, in practice, where "far-away" interference has to be considered as well, achievable performance might strongly differ from the bounds derived. Medium access strategies are not considered as well.

In [Ma et al. 2009] an analytical approach to derive the performance and reliability of broadcast transmissions for safety applications is presented. Yet, the study does not consider the capacity considerations presented in this thesis.

A simulation-based approach towards an assessment of local broadcasts and the comparability of different configurations is provided by the concept of *communication density* in [Jiang et al. 2007]. In periodic one-hop broadcast scenarios communication density is the multiple of node density, communication range and message generation rate, while packet size is assumed to be constant. It is shown that scenarios with similar communication density and identical communication range behave similar. In contrast to this thesis, however, it is not discussed to what extent the capacity may be used; instead it is discussed which scenarios can be seen being comparable in performance.

4.2 Formalization of requirements and conditions

In this chapter we introduce the different input variables that either define the system under consideration, describe the requirements given by the applications or represent configuration parameters with which the communication system and the exchange of messages can be controlled. We need this description in order to clarify the areas of influence and in order to perform the system analysis in the next sections.

Scenario and system constraints

As it was derived in Chapter 2.3 a communication pattern that provides local exchange of information among vehicles in a close neighborhood and in a reliable manner is one of the communication elements that is needed for V2X communication, in particular with respect to the high reception rates that are necessary in close distance. Safety applications need reliable and timely information to construct their local awareness, i.e. their individual view on the current traffic situation. As mentioned before, all nodes share one communication channel that is able to provide a *data rate* of b bits per second at maximum, but has to be shared among all communicating nodes. The nodes have an average *vehicle density* d, expressing the average number of nodes per kilometer in the one-dimensional considerations that we will perform.

Application requirements

Application requirements have to be derived as presented in Section 2.3.1, thus, with respect to the applications that should be supported. With respect to the requirements, we refer to the EEBL example presented in the same section.

The messages are transmitted as broadcast messages and the set of intended receivers is defined as all nodes that are positioned within a circular area of radius r around each transmitter, the *awareness range*. Ideally, every single message should be received successfully by all nodes in the awareness range. As such a strict condition is hardly achievable, an *awareness range reception probability* for each individual message of p percent at all intended receivers has to be achieved instead. In particular, the reception probability in distance r has to exceed p. A fundamental problem arises as the transmission of data packets can be directly influenced, while, in contrast, the main interest is on the *reception* of such packets, that cannot be directly controlled. Consequently, the requirements cover the reception performance, and the transmissions have to be adjustment in order to fulfill them.

Description	Acronym	Value	Entity
Scenario			
Data rate	b	3.0	Mbps
Vehicle density	d	60	nodes/km
Requirements			
Awareness range	r	100.0	m
Awareness range reception probability	p	95	%
Parameters			
Message size	s	500	byte
Message generation rate	f	10	s^{-1}
Message transmission power	P_t	10.0	dBm

Table 4.1: Scenario definitions, requirements by an application, and parameters that can be adjusted

Configuration parameters

For data transmission there are two fundamental adjustment possibilities. First, different transmission powers can be used that influence how far a message propagates. Under (unrealistic) deterministic assumptions an *intended transmission distance* m is reached, thus, the size of the area to which a message is intended to be propagated. Second, the *load* l of data transmissions by each individual node can be adjusted, thus, the size of data transmissions multiplied by the frequency of the transmissions. The adjustment can be done by either adapting the *message size* s or the *message generation rate* f of the transmissions. Table 4.1 gives an exemplary set of scenario description, requirements, and parameter choices as they could be required and selected by the EEBL application.

Practically, there are constraints with respect to the flexibility of choice of configuration parameters: due to the requirements to be fulfilled, their choice may be restricted. We consider the case where parameters can be freely chosen in Section 4.4, and the constrained case is discussed in Section 4.5. In the next section we will introduce the concept of reflecting mentioned parameters and feasible configurations as a capacity definition.

4.3 Definition of local broadcasts capacity

In order to give a capacity definition that considers technology aspects for a system with multiple access and the goal of having locally restricted multiple receivers we make the following two assumptions on the underlying communication system:

- The system provides a wireless communication channel of specific bandwidth that, from the technical system specification, is capable to transport a specific amount of data bits per second at maximum, thus, that provides a maximum data bit rate b.
- We assume a system that is capable to handle *one single successful packet reception at a time*. Advanced schemes that allow multi-packet reception in parallel are not considered here.

The problem of local broadcasts is discussed from a receivers point of view. The density of nodes in a scenario is assumed to be homogeneous. In the one-dimensional case, d represents the expected number of nodes per kilometer.

Now we consider the requirements given by an application of the communication system: messages have to be received with probability p in distance r. We identify the amount of data that each node in the network is allowed to transmit such that these requirements are fulfilled as *Local Broadcasts Capacity* C_{LB}, defined in the following:

Definition 4.1. ***Local Broadcasts Capacity***

The Local Broadcasts Capacity C_{LB} *is defined as the amount of data that each node in a scenario with node density* d *and available data bit rate of the channel* b *may transmit per second such that at each receiver the awareness of its surrounding can theoretically be achieved, i.e.* p *percent of all messages transmitted from nodes within awareness range* r *can be received successfully.*

The definition of local broadcasts capacity allows to compare the performance under different scenarios as well as the feasibility of a system configuration to achieve the expected requirements. As we will derive in the next sections, we identify an upper bound and the worst case of possible communication channel usage, and we discuss the application of local broadcasts capacity under constrained conditions. In Chapter 6.5 we will present local broadcasts capacity for results empirically achieved by simulations.

4.4 Theoretic bounds of local broadcasts capacity

We first identify, under idealized assumptions, an upper bound as well as a worst case of local broadcasts capacity in the next two sections. In order to illustrate the results we will apply the following parameterization example: we assume a communication system that provides a data rate $b = 3$ Mbps/s in a scenario with a node density of $d = 140$ nodes/km $= 0.14$ nodes/m and a required awareness range of $r = 100$ m in which the reception probability p should be higher than 0.95.

4.4.1 Maximum local broadcasts capacity

We first consider the maximum local broadcasts capacity $C_{\mathrm{LB,max}}$ that a wireless communication system could theoretically provide over a limited resource, the communication channel. We therefore model the system under strongly idealized and coordinated assumptions. Idealization is assumed with respect to radio propagation: a transmitted signal can be successfully decoded up to a specific distance, and additionally, the signal does not have any influence at nodes positioned further away. Idealization is also assumed with respect to node distribution: a homogeneous distribution of static nodes, i.e. equal distances between nodes aligned along one line is assumed. Perfect coordination not causing any additional overhead is assumed with respect to medium access: all nodes follow a perfect time schedule such that two transmitted packets never overlap and thus never collide. A basic principle that is always assumed to hold in the theoretic considerations is the assumption of a maximum of one packet reception at a node per time.

Figure 4.2 sketches the different factors of influence for the one-dimensional setup. We observe that each arbitrarily chosen receiver Rx must be capable to receive messages from all the nodes positioned a maximum of r away, thus, from nodes placed on a line of length $2r$. With a node density of d, the expected number of such nodes is $2rd$. As only one message per time interval can be received successfully, the available bit rate b has to be shared by the $2rd$ nodes, and one node at maximum is allowed to transmit $\frac{w}{2rd}$ bits per second. Otherwise at least one packet from one of the nodes with the distance r from Rx would not be receivable successfully due to the insufficient amount of data rate, or in other words, an overlapping in time of at least two packets would not be avoidable. Consequently, the derived ratio is an upper bound on the achievable bit rate per node when considering a fair distribution of available bandwidth. In consequence, we can define the maximum local broadcasts capacity $C_{\mathrm{LB,max}}$ as:

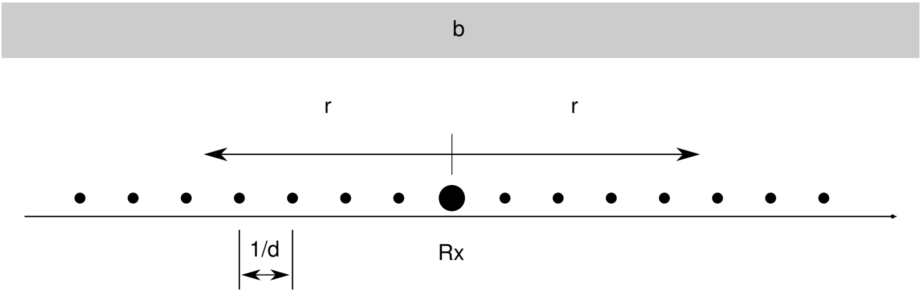

Figure 4.2: Sketch of the influencing factors of local broadcasts capacity. The perspective of receiver node Rx is taken, that wants to achieve awareness over all nodes in its surrounding of size r, where nodes are distributed with a density d, i.e. an average distance of d^{-1} between nodes in the one-dimensional case. In the actual scenario all of the shown nodes are receivers and the considerations are similar for each of them. The communication system uses a communication channel that can transport a data rate b at maximum.

Definition 4.2. ***Maximum Local Broadcasts Capacity***

The Maximum Local Broadcasts Capacity $C_{LB,max}$ *is calculated as:*

$$C_{LB,max}(b, d, r, p) = \frac{b}{2dr} \tag{4.2}$$

The variable b denotes the data rate in [bits/s] that the communication system is able to provide at maximum, d is the node density in [nodes/m] and r is the awareness range in [m] within which each node requires to receive periodic status information updated. p represents the required probability of reception within the awareness range. As we can see, $C_{\mathrm{LB,max}}$ does not use this information such that it can be set to the best possible value, thus, p=1: $C_{\mathrm{LB,max}}(b, d, r, p) = C_{\mathrm{LB,max}}(b, d, r, p := 1)$.

Maximum local broadcasts capacity $C_{\mathrm{LB,max}}$ reflects the maximum amount of data per second that a node may deliver to the medium, respecting that all other nodes behave the similar, while not over-saturating the channel within the awareness range of a node. One factor that restricts the performance is the assumption that at maximum one packet per time can be successfully handled by any receiver, thus, limiting the number of packets that a channel can transmit. This number of packets has to be distributed among all nodes expected to provide data, leading to the theoretical local broadcasts capacity limit. Figure 4.3 shows local broadcasts capacity for a one-dimensional scenario in dependence of the parameters r and d for a fixed data rate $b = 3\,\mathrm{Mbps}$.

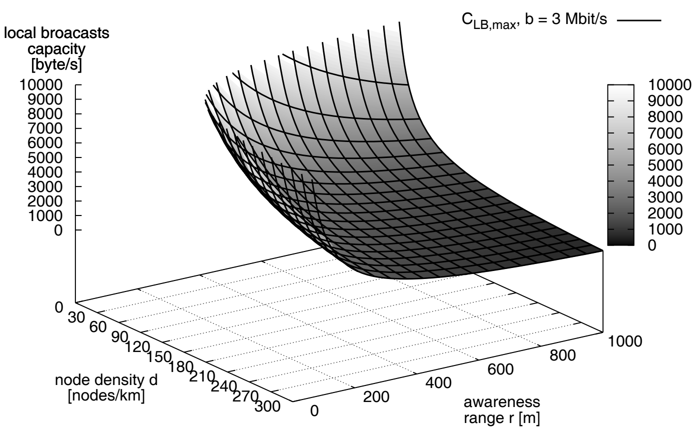

Figure 4.3: Local broadcasts capacity for a system that provides a maximum data rate of $b = 3$ Mbps. The maximum achievable data rate per node $C_{LB,max}(b, d, r)$ in [bit/s] is shown, where r is the required range of awareness in meter and d is the node density, here expressed in nodes per meter. The area below $C_{LB,max}$ contains all combinations of r and d that are theoretically achievable, while the area above conflicts with the capacity limit.

In case of the example parameterization we achieve the following result (result values rounded):

$$\begin{aligned}C_{LB,max}(b, d, r, p = 1) &= C_{LB,max}(3 \cdot 10^6, 0.14, 100, 1)\\ &= 107,142 \text{ bit/s}\\ &= 13,392 \text{ byte/s}\end{aligned}$$

The local broadcasts capacity thus expresses that for the given configuration each node may at maximum provide 13,392 byte/s to the medium, e.g. in form of 10 packets per second, each of maximum size 1,339 byte.

4.4.2 Worst case local broadcasts capacity

The worst case local broadcasts capacity $C_{LB,wc}$ affords more effort with respect to its definition and derivation. Trivially, the lowest achievable rate that a node may provide is 0 bit/s. Yet, with this rate, any requirement from applications that requests communication between the nodes would not be fulfilled, and consequently the "zero rate" would not provide a feasible solution. What is instead done here is that we assume non-ideal and uncoordinated conditions in the following, to a degree that cannot be worse from communications point of view. Non-ideal conditions are considered with respect to radio propagation: we assume that a

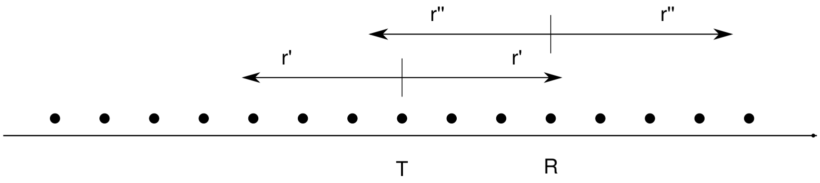

Figure 4.4: Sketch of the system setup for the worst case study.

transmission affects nodes in a large range. An even worse assumption would be that any node is affected by a transmission. Yet, that would makes any worst case consideration meaningless and would lead to infeasability of any system configuration as the number of affected nodes could not be derived. Uncoordinated conditions are considered with respect to medium access behavior: we assume that the nodes do not coordinate at all, but transmit their packets randomly, without respecting the behavior of other nodes; the only worse strategy would be "forced collisions" of packets, i.e. transmission of packets when collisions on the channel are the unavoidable consequence. Thus, we actually consider the "most uncoordinated" but "still meaningful" situation.

As mentioned, we consider a system model in which we assume that medium access is done randomly without sensing whether a transmission from another node is currently ongoing. This random access scheme is known as the ALOHA strategy, first discussed in [Abramson 1970]. We further assume that a transmitted message can, under best conditions, i.e. without being interfered, be received by all nodes in a radius r' (reception range) around the transmitter. A reception is considered being successful if there was no other timely overlapping transmission within radius r'' (interference range) around each receiver, see Figure 4.4 that indicates an arbitrary transmitter Tx and the corresponding transmission range of absolute size $2r'$ as well as a receiver Rx and the interference area of absolute size $2r''$ within which two timely overlapping transmissions would collide and avoid a successful reception. In our considerations we ignore propagation delays, thus, we assume that the moment of transmission is equal to the moment of reception at all nodes. Note that we still argue with deterministic and fixed radio ranges here.

We now discuss $C_{LB,wc}$, the data rate that each node may use under the described uncoordinated conditions. We assume that the maximum data rate b, the node density d and the expected awareness range r are provided similar to the definition for maximum capacity. Additionally, we derive the following relations. The load l of each node is the multiple of the size s of each data packet and the rate f with which packets are transmitted, thus $l = sf$. As b is the effective data rate that can be provided by the communication system we can determine the duration τ that a data packet needs to be transmitted: $\tau = \frac{s}{b}$.

We identify the number of nodes g that are possible receivers of a message transmission as $g = 2dr'$. As broadcast messages should be transmitted to all nodes within distance r a broadcast is considered as successful if none of the intended receivers is interfered by another node's transmission. A broadcast is considered being failed if one or more nodes are interfered by another transmission. All nodes within the awareness range r may possibly be interfered. Particularly the nodes positioned at the edge of the awareness range, thus in distances close to r, may be affected by any other transmission from nodes within distance r'' away from them. Thus, in order to perform a successful broadcast, no other transmission from nodes within distance $r + r''$ from the transmitter may overlap in time. In consequence, taking the two directions of the one-dimensional scenario, the range h in which possibly interfering nodes for broadcast transmission are positioned is $h = 2(r + r'')$.

If one packet is transmitted we observe a collision at a specific receiver if any other packet from a node within r'' overlaps in time. If transmission starts at time t and lasts for duration τ, then an overlap occurs for messages transmitted within the time interval $[t - \tau, t + \tau]$, i.e. a duration of 2τ. Thus, in order to determine the success probability of a packet transmission at all intended receivers of a broadcast transmission, we have to derive the probability that no node in range h transmits for a duration of 2τ. We now assume that the start times of message transmissions of nodes are independent of each other and exponentially distributed with the average transmission rate f. The assumption of exponentially distributed average transmission rates is simplified and relates to ALOHA where random start times of transmissions are assumed. Then, the probability p that there will be no transmissions for a duration δ (here $\delta = 2\tau$) and for a number ω of expected transmissions per time unit (here $\omega = fdh$) is $e^{-\delta\omega}$, see [Abramson 1970]. Applied to the scenario we achieve:

$$p = e^{-\delta\omega} = e^{-2\tau \cdot fdh} = e^{-4fd\tau(r+r'')}. \tag{4.3}$$

From Equation 4.3 we observe that the probability of a successful broadcast reception depends on several factors. Under the simplifying assumption that r and r'' are equal, i.e. the required reception range and the interference range are identical, we achieve the probability of a successful broadcast as:

$$p = e^{-8df\tau r}. \tag{4.4}$$

By substitutions and transformations we can derive $C_{LB,wc}$, the data rate with which the requirements can be fulfilled:

$$\begin{aligned} \ln p &= -8df\tau r = -\frac{8dfrs}{b} = -\frac{8drl}{b} && (4.5) \\ l &= -\frac{b \ln p}{8dr} && (4.6) \\ &= \frac{b}{2dr} \cdot \left(-\frac{\ln p}{4}\right) && (4.7) \\ &= C_{\mathrm{LB,max}}(b, d, r, p := 1) \cdot \left(-\frac{\ln p}{4}\right) && (4.8) \end{aligned}$$

As l is the maximum achievable data rate under the given conditions we can define:

Definition 4.3. ***Worst Case Local Broadcasts Capacity*** *The Worst Case Broadcasts Capacity* $C_{LB,wc}$ *is calculated as:*

$$C_{LB,wc}(b, d, r, p) = C_{LB,max}(b, d, r, p := 1) \cdot \left(-\frac{\ln p}{4}\right) \tag{4.9}$$

As we can see from Equation 4.8, $C_{\mathrm{LB,wc}}$ is a fraction of $C_{\mathrm{LB,max}}$ and depends on p, the expected probability that the reception is successful within the awareness range. For $p \to 1$ yet, $l \to 0$, thus, there is not any achievable data rate with which successful reception at all nodes can be reliably achieved. In consequence, values can be identified only for high success probabilities. Exemplary a factor of 0.0025 is achieved when $p = 0.99$, and 0.026 for $p = 0.90$. In Figure 4.5 the ratio between $C_{\mathrm{LB,max}}$ to $C_{\mathrm{LB,wc}}$ is shown for varying reception probability p.

We observe that the worst case capacity only uses a very small amount of theoretically provided maximum capacity. Figure 4.6 shows $C_{\mathrm{LB,max}}$ and $C_{\mathrm{LB,wc}}$ in comparison, the achievable data rate under perfectly coordinated and completely uncoordinated conditions. The z axes expressing the capacity is shown in logarithmic scale, thus, the ratio between worst case and maximum data rate is much more drastic than can be derived from the figure.

In case of the example parameterization we have to additionally define the reception probability p. We now assume $p = 0.95$. With these parameters we achieve the following result:

$$\begin{aligned} C_{\mathrm{LB,wc}}(b, d, r, p) &= C_{\mathrm{LB,wc}}(3 \cdot 10^6, 0.14, 100, 0.95) \\ &= 1{,}373 \text{ bit/s} \\ &= 171 \text{ byte/s} \end{aligned}$$

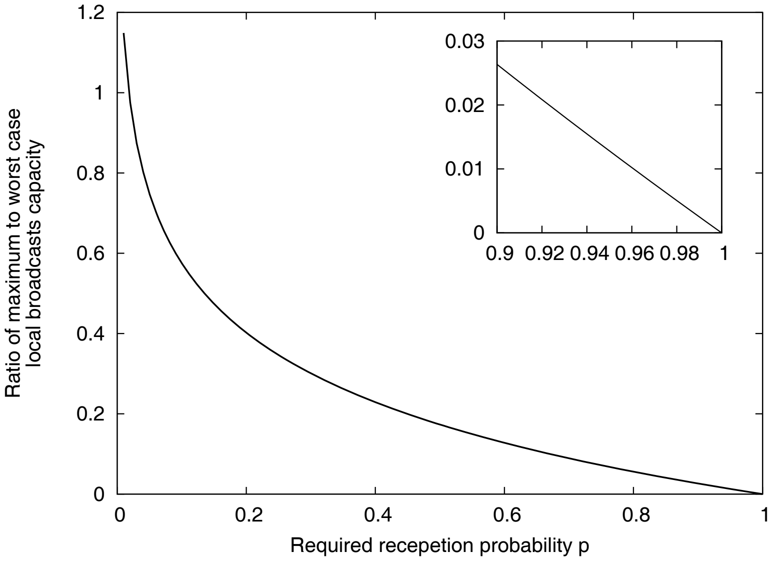

Figure 4.5: Ratio of $C_{LB,max}$ and $C_{LB,wc}$ with respect to p, the required reception probability in the awareness range

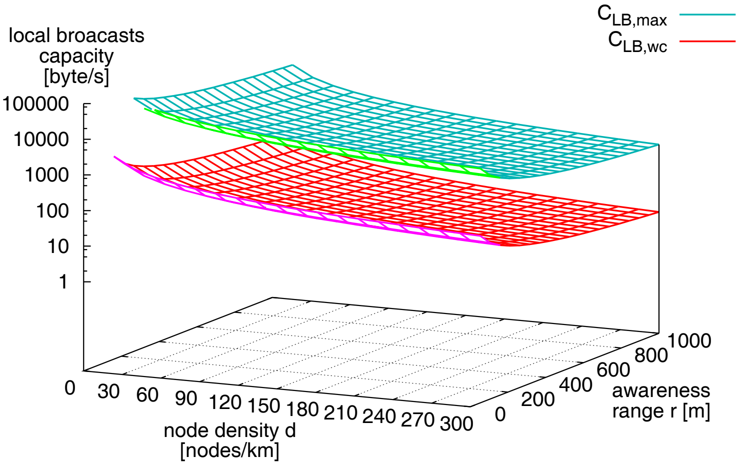

Figure 4.6: Comparison of maximum and worst case local broadcasts capacity.

The local broadcasts capacity thus expresses that for the given configuration each node may at maximum provide 171 byte/s to the medium, e.g. in form of 10 packets per second, each of maximum size 17 byte. It is obvious that the worst case values reflect very low performance.

4.5 Local broadcasts capacity under constraints

In the last section, local broadcasts capacity was considered with respect to its boundaries. The maximum local broadcasts capacity $C_{LB,max}(b, d, r, p := 1)$ was derived under the assumption of perfect coordination between the nodes, what can hardly be fulfilled in a decentralized and distributed system in reality. The worst case local broadcasts capacity $C_{LB,wc}(b, d, r, p)$ was derived for a system that uses the communication without considering any coordination among the nodes. Both considerations consider extreme cases that do not represent what can be expected for an applied system. In the following, we review the application requirements and how these restrict the number of allowed configurations to specific subsets. In consequence the achievable data rates may be restricted as well and lead to a lower local broadcasts capacity compared to the unconstrained case.

Until now, local broadcasts capacity directly considered one specific and fundamental requirement of applications: providing an awareness range in the surrounding of each receiver, i.e. the receiver is aware of all nodes with the awareness range due to regular status messages. Local broadcasts capacity defines for a specific awareness range r and for a reception probability p that has to be reached the number of bits per second that each node may provide to the communication channel.

First, there are more requirements that need to be considered. For example, a maximum delay of messages has to be guaranteed, or, a maximum inter-arrival time between messages from one transmitter node may not be exceeded. Further, a minimum number of update messages has to be received from each node in awareness range per time interval. Such additional requirements restrict the configuration combination that may be applied to use the communication system and excludes configuration combinations that do not provide the required performance. In consequence, the achievable local broadcast capacity is then restricted to these acceptable configuration combinations, and the local broadcasts capacity may not be as good as if an arbitrary configuration can be chosen.

Second, the communication itself requires minimum necessities. For example, the size of transmitted data packets may not be chosen arbitrarily small as obviously some content should be transmitted, and additionally, each frame inherits some overhead. If we obtain a specific local broadcasts capacity, and if a minimum

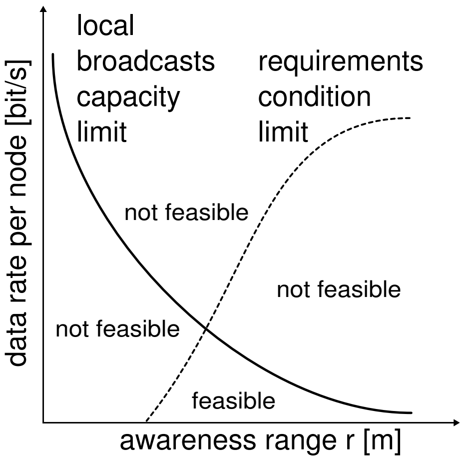

Figure 4.7: Principle sketch of local broadcasts capacity and additional constraints under the assumption of a fixed node density d_1. The combination of parameters with achievable capacity and fulfilled requirements forms the set of feasible system parameters.

size of data frames is required, then these two reasons lead to a maximum number of frame transmissions per node and time interval. The restricted number of transmission may in consequence lead to missing one of the communication requirements mentioned in the last paragraph, e.g. with respect to the update rate from each node. Consequently, application requirement can lead to the situation that constrained local broadcasts capacity does not have any applicable solution.

By combining the additional restrictions and C_{LB} we derive a set of feasible configurations in which both local broadcasts capacity and the required conditions are fulfilled, i.e. that the system is neither over-saturated, nor are the requirements missed. Within this set system operation is possible and an optimal configuration can be identified by additionally given metrics. It is also possible that there are some scenarios for which the set of feasible configurations is empty. Consequently, the corresponding model claims that it is infeasible to operate the communication system with the given parameters and thereby fulfill local broadcasts capacity. Figure 4.7 gives a principle sketch of a constrained local broadcasts capacity for one varying parameter, here the awareness range, while the other parameters are fixed: it visualizes the borderlines for the two conditions and indicates the feasible operation area of the system.

Reconsidering the example parameterization, we additionally introduce constraints. As it was derived before in the constraint-less extreme cases we achieve:

$$C_{LB,max}(3 \cdot 10^6, 0.14, 100, p := 1) = 13,392 \text{ byte/s} \tag{4.10}$$

and

$$C_{\mathrm{LB,wc}}(3 \cdot 10^6, 0.14, 100, 0.95) = 171 \text{ byte/s}. \tag{4.11}$$

If additional requirements from the applications request a generation rate of 10 packets per second and a packet size of 400 byte is necessary to include all information and security information, we see that the constraints would be fulfilled if a communication system could provide the capacity calculated by $C_{\mathrm{LB,max}}$, but it could not fulfill the requirements in case of a performance related to $C_{\mathrm{LB,wc}}$. As we see from this example it is of very high interest what level of local broadcasts capacity a particular communication system is able to provide, and whether the constraints would be fulfillable, or not.

4.6 Summary

The definition of *local broadcasts capacity* is motivated by the specifics that we observe when investigating V2V communication. We see that the usually applied concepts to describe the radio channel, its usage and its characteristics do not cover the needs that have to be respected in vehicular networks. The central problem arises in sharing one single channel between all participating vehicles such that each of the vehicles is able to provide its own current status as a local broadcast packet to all vehicles in its the awareness range.

Under simple system assumptions, we can derive maximum and a worst case local broadcasts capacity. The challenge with more advanced models lies in their complexity that does not or only hardly allow analytical considerations due to the much stronger inter-dependencies between systems and system states and due to the unreliability of the wireless channel. In consequence, we will later in Chapter 5 derive models of the communication system that can be used within simulations. The simulations are then used in Chapter 6 to analyze the influence of different modeling on local broadcasts capacity, and to identify what capacity can be achieved by the IEEE 802.11p communication system that will be applied for V2V communication.

5

Modeling and simulation of vehicle-to-vehicle communication networks

In this chapter we present the efforts made in order to provide detailed models of V2V communication networks and their application in simulations to perform simulation studies. The goal of the studies is a fundamental performance evaluation for the systems and applications presented in Chapter 2, respecting the considerations presented in Chapter 3 and comparing the observed results to the ones discussed in Chapter 4.

The chapter is organized as follows. First we introduce the methodology of modeling and simulations and discuss the important issues that have to be considered and kept in mind when doing simulation studies. We then explain the models that are used for the simulation studies, in particular with respect to modeling radio propagation and receiver characteristics. The capture capability is one central point of the modeling consideration. Then, we will focus on the tool that is used for implementing the models and investigating V2V network performance evaluations, the Network Simulator 2 (NS-2). In particular, we will present the efforts made to achieve an overhaul of the models and the simulation implementation of the PHY and MAC layer that provided an important step towards more realistic modeling of lower communication layers in network simulators.

The results of this chapter are applied in Chapter 6 where the different aspects and effects of modeling and simulation are considered and the performance of V2V communication is evaluated with particular focus on local broadcast communication. This chapter delivers the solid foundation for later simulation experiments and is mainly based on the publications [Schmidt-Eisenlohr et al. 2007] and [Chen et al. 2007], as well as on the technical reports [Schmidt-Eisenlohr et al. 2006a] and [Schmidt-Eisenlohr et al. 2006b].

5.1 The modeling and simulation process

Modeling and simulation is an often used strategy in order to analyze and evaluate the performance of systems. The books [Law 2007] and [Birta & Arbez 2007] introduce the topic and discuss major issues with respect to modeling, stochastics, evaluation and the credibility of results of simulation studies. Key issue with respect to simulation and modeling are the appropriate way of modeling and respecting the laws of stochastics in order to achieve a correct and valuable interpretation of results.

Several publications consider the way of modeling and evaluation and discuss the credibility and reliability of simulation results. From the application domain of communication networks very prominent publications are [Kurkowski et al. 2005] and [Pawlikowski 2003]: in both publications, major shortcomings with respect to the way of modeling are shown. The studies also show that there is a shortcoming with respect to publishing all relevant statistical numbers and assumptions, what would allow a better reproducibility of simulation results. [Ören et al. 2002] defines a generic approach of an ethics code for simulationists with the goal of achieving reliable, valid and reproducible results of simulation studies. A procedure for verification and validation of simulation models is described in [Sargent 2008].

One achievement of this work is that we make use of detailed models and provide a precise description of the models used. The code used for the implementation of the simulations is completely publicly available and can be reviewed by other researchers as well, see [WWW NS-2Ext]. Further, we provide stochastically significant results and present all input parameters and stochastic values in order to provide statistically valid simulation results in the next chapter. In this chapter, however, we first discuss the modeling assumptions and present the models that were used. The complete simulation process has to be carefully followed in order to achieve valuable results.

5.2 Fundamental modeling aspects

In [Schmidt-Eisenlohr & Killat 2008] we, among other content, described the aspects that are important with respect to simulation and modeling of V2V networks in order to allow a detailed performance evaluation. This section follows the discussion published in [Schmidt-Eisenlohr & Killat 2008] and emphasizes the major issues already reviewed from a theoretic standpoint in the chapters before with respect to modeling and simulation.

Since "full-physics simulations" cannot be performed for network communication research, we depend on abstractions that appropriately represent the characteristics of communication in a vehicular environment. This modeling process directly raises the question of what is appropriately modeled and what leads to incorrect simulation results. In the following these questions will be discussed for three aspects in wireless systems: modeling of physical behavior, influence of technological advancements and improvements to existing simulation components. Namely, we discuss the influence of radio wave propagation, the capturing effect and cumulative interferences. All effects are often neglected in simulation studies of V2X communication networks.

5.2.1 Radio propagation and fading

As presented in Section 3.1, radio wave propagation strongly depends on environmental influences and its modeling can be done in different manners and levels of detail. Often, too simplistic models are chosen that hardly represent the system characteristics found in reality. Such models typically have deterministic characteristics, i.e., for a fixed distance between transmitter and receiver the calculated reception power is constant and does not change. However, as environmental influences can hardly be modeled in a deterministic manner, more advanced models with non-deterministic reception characteristics have to be applied. Thereby, the calculated reception power varies for each transmission and at each receiver.

As discussed in Section 3.1.2, the Free Space and the Two Ray Ground propagation model [Rappaport 2002] are well known deterministic radio models. In both models the reception power steadily decreases with increasing distance between transmitter and receiver node. A flexible and adjustable non-deterministic model that resembles small-scale fading uses the Nakagami-m distribution as underlying probability distribution [Nakagami 1960], see Section 3.1.3. First the average reception power is determined by means of a deterministic path loss model. Following Rappaport's suggestion [Rappaport 2002], the Free Space model is applied in closer distances and the Two Ray Ground model in distances that exceed a given threshold, called crossover distance. By utilizing the average power the

Nakagami-m distribution finally determines the strength of each individual radio signal in a probabilistic manner. The m-parameter allows the coverage of a wide range of fading intensities, and e.g. in [Taliwal et al. 2004] it is shown that with properly chosen parameters this model is suitable to reflect the characteristics of vehicle-to-vehicle communication on highways. The resulting reception characteristics will be further discussed in Section 6.3.1.

5.2.2 Capture effect

In IEEE 802.11 based networks, packets transmitted over the wireless channel always start with a fixed preamble sequence that allows potential receivers to detect the beginning of a packet. In case a radio chip detects the preamble sequence it tries to decode the succeeding packet header. The packet header includes all the necessary information to retrieve the following payload of the packet. Only in case the information can be successfully decoded, the chipset is then able to lock on the reception of that packet until its end.

Advanced radio chips support capturing technologies. In addition to the procedure just described a packet reception can be interrupted in case a much stronger preamble of another packet is observed during the reception phase. Radio chips differ in the extent of supporting capturing techniques. Some only allow capturing during the preamble and header reception phase, others additionally during payload reception. Depending on a threshold the chip either continues the reception of the ongoing packet or switches to the newly arriving packet. The advantage of such technology is observable for low-distance transmissions, as such transmissions cause a much stronger reception power and can dominate far-distance transmissions. For a further discussion we refer to Section 5.3.4 and to Section 6.3.3.

5.2.3 Interferences

Several concepts exist to model interferences between parallel ongoing radio transmissions, thus, multi-user interference as described in Section 3.2. Simplified, parallel transmissions are not considered at all. Or, on the other extreme, any overlapping transmission implies unsuccessful packet receptions. Ideally, each node in a simulation keeps track of all currently ongoing transmissions as illustrated in Figure 5.1. Successful or unsuccessful reception of a packet is determined by means of signal to interference and noise ratio (SINR) while considering the sum of all ongoing transmissions as cumulative interference.

The standard release of NS-2 considers the reception power of the longest packet still being present on the medium as the level of interferences, whereas all other ongoing transmissions are ignored. Consequently, the overall noise level

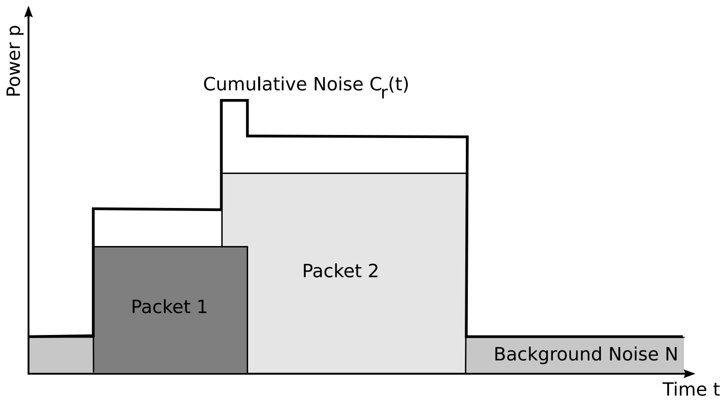

Figure 5.1: Illustration of the cumulative noise model. The figure is not to scale.

is wrongly assessed and, thus, leads to an overestimated quality of the communication channel. A further discussion of this issue is provided in Section 5.3.3 and considered in the complete study in Chapter 6.

5.3 Modeling of the IEEE 802.11p PHY layer

This section describes details of the IEEE 802.11 transmissions and receptions at a level that is meaningful for simulator designs. This overview is intended to demonstrate the importance of proper preamble and PLCP header handling in the simulation design. Some issues were already mentioned in the general description of IEEE 802.11 in Section 2.4.2, yet, we emphasize the details again as they have strong impact on the simulation model, see also [Chen et al. 2007] where the following considerations was presented first.

5.3.1 Modulation and coding rate

The perceivable data rates of IEEE 802.11 radios are determined by modulation and coding rate used in transmissions. Modulation is the method in varying a periodic waveform in order to convey some information. As shown in Table 5.1, which lists all the defined transmission options for IEEE 802.11a radios, the BPSK modulation method is able to convey 1 bit of information per periodic waveform per sub-carrier. Because IEEE 802.11a radios transmit data over 48 sub-carriers concurrently in its OFDM design, BPSK allows each OFDM symbol to carry 48 bit of information. Coding rate describes the fraction of the total carried bits that is used for actual data bits. The rest are redundancies used to correct errors in the reception process. For a 20 MHz channel, each periodic waveform (plus a guard interval to prevent inter-symbol interference) takes 4 μs to send. Therefore, the

Data rate	Modulation Scheme	Coding Rate	SINR Threshold [dB]
3	BPSK	1/2	5
4.5	BPSK	3/4	6
6	QBPSK	1/2	8
9	QPSK	3/4	11
12	16-QAM	1/2	15
18	16-QAM	3/4	20
24	64-QAM	2/3	25
27	64-QAM	3/4	N/A

Table 5.1: Data rate, modulation scheme and coding rate used in IEEE 802.11p as defined in the standard. Additionally, the SINR thresholds needed to achieve successful packet reception in the simulations are given, see [Jiang et al. 2008])

combination of BPSK modulation with 1/2 coding rate results in the 6 Mbps baseline data rate supported by IEEE 802.11a radios. In IEEE 802.11p, 10 MHz channels are used, resulting in symbol durations of 8 µs and a basic data rate of 3 Mbps.

While a higher level of modulation and coding rate combination provide a higher data rate, the reception of such a frame is more likely subject to errors. In other words, it needs a cleaner and stronger received signal to successfully receive such a frame.

5.3.2 PHY layer frame structure

A transmitter may select any defined modulation and coding rate combination to transmit a frame at any time as regulated by the MAC protocols. A receiver, however, needs to be able to know if the signal on the channel is a frame instead of noise, how long the frame duration is and what modulation and code rate combination is used, in order to have an opportunity to successfully receive a frame.

As shown in Figure 5.2, the PHY layer frame always starts with a known training sequence called preamble to notify receivers on the arrival of a frame and assist them to lock on to the signal. The preamble is followed by a physical layer convergence protocol (PLCP) header, which contains details on the frame body including modulation and coding rate, frame length, etc. The preamble and the front part (i.e. Signal portion) of the PLCP header are both modulated by BPSK in almost all IEEE 802.11 radio configurations. While the preamble has no coding rate, the Signal part of the PLCP header is coded at 1/2 rate. The frame payload follows the PLCP header and is demodulated and decoded by the receivers according to the information contained in the Signal portion of the PLCP header.

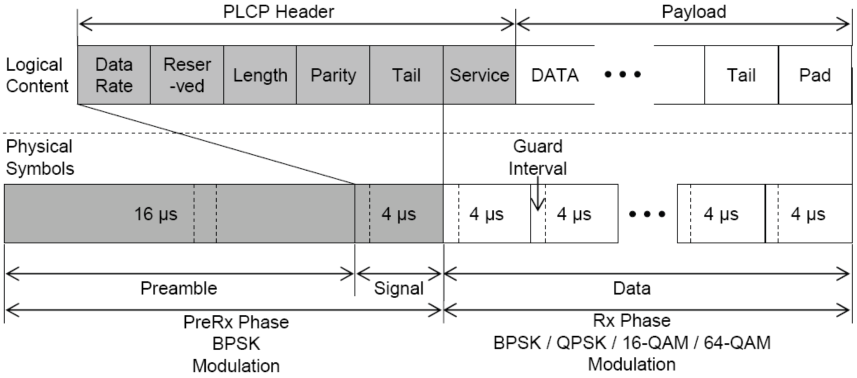

Figure 5.2: Structure of an IEEE 802.11a frame. For IEEE 802.11p all shown durations are doubled.

5.3.3 Frame reception process

A group of interacting IEEE 802.11 radios shares one channel for communications. In general, wireless radios are not able to send and receive simultaneously in the same channel. Therefore, a radio is always in one and only one of three conditions: listening on the channel to look for incoming frames, transmitting a frame when commanded by the MAC, and (attempting in) receiving a frame.

As a radio listens on the channel, it continuously looks for the known pattern of the preamble by demodulating the received signal according to the BPSK method. If such a pattern is found, the receiver will attempt to decode the Signal portion of the PLCP header. If this attempt is again successful, the receiver is then committed to demodulate the received RF waveforms for the frame duration according to the information recovered in the Signal portion of the PLCP header. From this point on to the end of the frame duration, the receiver treats all received signal as belonging to the incoming frame and attempts to demodulate it. The resulting raw bits will be given to the MAC for CRC check to finally determine if a frame is successfully received. If a frame arrives when the node is in transmission, it will not be able to hear this frame. Even if its transmission state would end very soon after, this radio would not be able to receive the incoming frame because it would have missed the critical preamble and PLCP header and have no information to receive the frame body.

Similarly, if a node is already in the frame body reception process, it will not be able to receive an incoming frame because the node would treat the signal from the new frame as from the frame currently being received. Since the node is not looking for the preamble of a new frame, it will not realize that a new frame has arrived. If the new frame has strong enough signal strength, it will collide with the existing frame and prevents its successful reception. In case that the capture capability is activated such a new frame may still be received, see also Section 5.3.4.

Because the frame body may be transmitted with a modulation and coding rate combination different from the BPSK and 1/2 coding rate used for the signal portion of the PLCP header, it is possible that a receiver is able to receive and decode the preamble and PLCP header correctly, yet still fails during the subsequent reception of the frame body itself, depending on the signal quality and interferences.

5.3.4 Capture

The IEEE 802.11 radios are designed to be very robust in the process of searching for and decoding the preamble and PLCP header. That is: if a new frame arrives when the receiver node is still receiving the preamble and PLCP header of an earlier frame, the new frame can be picked and locked onto by the receiver node if it has sufficiently higher power to be heard above the earlier one. This preamble capture feature is generally present in the IEEE 802.11 chips but is not widely modeled in the simulators. Further, it is also possible to capture a new incoming frame during the payload reception process of another frame. Payload capture is not part of the IEEE 802.11 standard but is implemented in some chips as an optional feature. In the rest of this document we define *preamble/header capture* being solely the first type of capture described and *full capture* being both, the first and the second type of capture described.

This feature works by having the PHY continuously monitor the received signal strength over the air. If there is suddenly a sharp rise (e.g. by 10 dB), the receiver assumes this is caused by the arrival of a new and much stronger frame. It then immediately abandons the previous frame and attempts to decode the preamble and PLCP header of the new frame. If successful, it then starts the reception process for the new frame. A description of the capture mechanism and technology is given in the patent [Boer et al. 1999].

5.4 The Network Simulator 2 (NS-2)

We now introduce the simulator of choice for our further discussions, the Network Simulator 2 (NS-2). The versions that were available had several drawbacks that were overcome during this research work. We first give an overview of the drawbacks and then concentrate in the fundamental improvements that are in the center of this thesis in the next section. The following considerations refer to the NS-2 version 2.32.

5.4.1 NS-2 limitations

The design of the default NS-2 wireless implementation is shown in Figure 5.3. It consists of several layered modules that are interconnected by simple interfaces for passing packets up and down along the layers. Design and responsibilities of each of the modules are briefly described below.

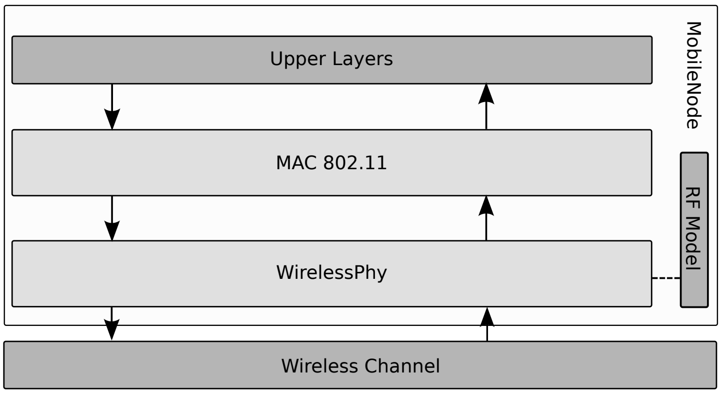

Figure 5.3: Structure of a NS-2 mobile node.

WirelessChannel: The module interconnects all wireless nodes in a simulation scenario and interchanges frames among them. Its only functions are to pass frames from each sender to all possible receivers, creating an exclusive copy for each of them and to handle the propagation delay on the channel. It does not handle interferences, collisions, or path loss calculations.

WirelessPhy: The module takes the frames coming from the wireless channel and requests for each of them the actual reception power Pt from the RF model object described in next section. If Pt is greater than the Carrier Sense Threshold, the frame is passed to the Mac802.11 module where all further handling is done. When a packet comes from the MAC, it is passed to the WirelessChannel module.

RF model: A specific radio propagation model is taken to determine the reception power for each packet. The individual power depends on the selected model, and is, among other factors, depending on the distance between transmitter and receiver.

MAC 802.11: The module contains most of the complexities in IEEE 802.11 modeling. It not only handles the coordination of channel access for transmissions (which is appropriate for a MAC module), but also determines physical packet reception and collision management (which should be handled by the PHY module).

A huge drawback of this implementation is structural in nature. Most of the PHY functionalities are mixed up in the MAC. As a result, it is very difficult, if not impossible, to model everything correctly at both the physical and logical levels. The overly complex MAC module is also a big challenge for the users to understand and extend in their researches. There are many instances of oversimplification or inaccuracies in the IEEE 802.11 modeling, see our technical reports [Schmidt-Eisenlohr et al. 2006a] and [Schmidt-Eisenlohr et al. 2006b]. The major weaknesses of modeling are wrong collision handling, no preamble and PLCP header modeling, no cumulative SINR implementation, wrong backoff handling, the misusage of the network allocation vector (e.g. for EIFS), and an incomplete support of capture capabilities.

A major weak aspect relates to the interference and reception model. The wireless interface implemented in ns-2.32 is based on three power related thresholds:

- *Carrier Sense Threshold (CSTh)*: A message that arrives at a wireless interface of a node with a power lower than CSTh will not be sensed. A message arriving with power equal to or higher than CSTh is sensed by the wireless interfaces and the medium is determined *busy*.
- *Receiving Threshold (RxTh)*: A message arriving with a power equal to or higher than RxTh in the absence of interferences can be successfully received.
- *Capture Threshold (CpTh)*: A message with power equal to or higher than RxTh can be successfully received in the presence of interferences if the following two conditions are fulfilled:
  i) the packet arrives at the interface while the medium is *idle*
  ii) the power of the packet is CpTh above the power of the strongest interference occurring during the reception of the packet. A packet arriving while the medium is already *busy* is never received successfully.

Additionally, the default implementation of ns-2.32 can only handle one incoming packet at a time, referred to in this document as the *current packet*. This way, at the moment that a packet is being received and a new one arrives a decision must be taken with respect to which packet, together with its corresponding information (received power, length, etc.), will be kept by the system and which one will be discarded.

This design implies inaccuracies with respect to how packet reception and medium status detection is handled. With respect to condition *ii)* in the CpTh definition we observe the following:

- If condition *ii)* is satisfied, the reception process is continued and the current packet is kept, whereas the newly arriving one is discarded. If the newly arriving packet has a longer remaining reception time than the current packet, the medium status is indicated incorrectly at the end of a successful message reception, *idle* instead of *busy*.

  - If the condition is not satisfied, both packets collide and none of them can be received successfully. The packet having the longer remaining reception time is kept, while the other one is discarded.

Note that the power of the current packet is compared to the power of each newly arriving packet individually, neglecting the effect that power levels of several of such packets can sum up to a higher interfering power level.

Summarized, the interference and reception model of the standard implementation leads to the following two statements:

- The interference model determines the state of the medium by comparing the signal power S of the packet that is currently being received with $CSTh$: it is determined *idle* if either no packet is currently being received at all, or $S < CSTh$. It is determined *busy* if $S \geqslant CSTh$ holds for the signal power S of the received packet.
- The reception model indicates a successful reception of a packet X with signal power S, if the medium was *idle* at the start of reception and, during the complete reception time of X, its reception power S is $CpTh$ above the maximum power of the interfering packets, I_{max}, arriving during its reception time, i.e., $S \geqslant I_{max} + CpTh$ is always satisfied.

The drawbacks that were described in this section have been addressed and led to the overhauled simulator described in the following.

5.5 Overhaul of NS-2

In order to overcome the weaknesses we present a revised IEEE 802.11 modeling that fits into the overall NS-2 wireless simulation framework. The models and simulations were developed in close cooperation with Mercedes-Benz Research & Development North America in Palo Alto, California. That is, all nodes are attached to a common Wireless Channel object through the PHY. Whenever a node transmits, the channel notifies all attached nodes of the transmission event. Each node's PHY communicates with the RF Model object, which computes received signal strength for each incoming transmission using the selected RF propagation model and the node's own position.

The architecture of the IEEE 802.11 MAC and PHY modeling, as shown in Figure 5.4, is now completely different from the default NS-2 implementations. Instead of putting everything inside the MAC, all functionalities of the IEEE 802.11 radio are now cleanly and properly separated between the MAC and PHY.

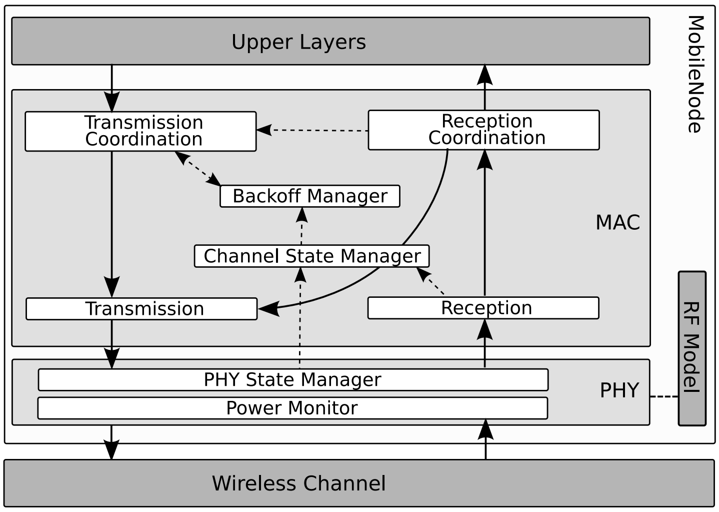

Figure 5.4: Structure of the overhauled NS-2 mobile node.

The MAC module now only operates at the logical level. It depends on the PHY to handle actual transmissions, receptions and physical channel sensing. The focus of the MAC design is to correctly and cleanly model all the complexities in the IEEE 802.11 CSMA/CA mechanism which is also known as distributed coordination function (DCF). A key purpose of this new design is to make it easy for users to understand and extend the MAC for their researches.

The PHY module handles all physical layer related issues, such as channel sensing, SINR tracking and PLCP state management. While the work on the PHY is part of the overall IEEE 802.11 modeling, its design is sufficiently generic so that it is able to support the implementation of different MAC designs on top. In the following subsections, all modules within the MAC and PHY are described.

In the following a complete IEEE 802.11 model is described, thus, also contain components like unicast specifics that may not be used directly in the V2V communication considerations that follow, thus, it is much more flexible than just for the use case under consideration in Chapter 6. The description has been adapted from our original publication [Chen et al. 2007].

5.5.1 Radio propagation model

The radio propagation models are applied as described in Section 5.2.1. The large-scale path loss models described in Section 3.1.2 are implemented as shown in the formulas. Achieving values that are distributed according to the pdfs of small-scale fading described in 3.1.3 is added to NS-2 as a distinct module that provides Nakagami-m radio propagation. The values observed were compared to the theoretically expected distribution of values and showed a perfect match.

5.5.2 Physical layer model

As shown in Figure 5.4, there are two modules placed in the PHY. The power monitor module keeps track of received RF signals from all the transmission events over the air. The PHY state manager is responsible to maintain PLCP states.

Power monitor: The power monitor module corresponds to the physical layer medium dependent (PMD) sub-layer within the PHY. PMD is the only sub-layer that directly interacts with the analog RF signals. Therefore, all information on received signals is processed and managed in this module.

The power monitor module keeps track of all the noise and interferences experienced by the node individually for their respective durations. Whenever the cumulative interference and noise level crosses the carrier sense threshold (CSTh), it signals the MAC on physical carrier sense status changes. It should be noted that a node's own transmission is treated as carrier sense busy through this signaling interface as well.

PHY state manager: The PHY state manager models the PLCP sub-layer, which is the logic sub-layer of the PHY. The state manager keeps track of how the PHY switches among four operating modes.

The PHY is in the Searching state when it is neither in transmission nor reception of a frame. Within this state, the PHY evaluates each transmission event notification from the Wireless Channel object it is attached to for potentially receivable frames. If a frame arrives with sufficient received signal strength for preamble detection (i.e. SINR > BPSK threshold), the PHY moves into the PreRXing state.

The PHY stays in the PreRXing state for the duration of preamble and Signal portion of the PLCP header. If the SINR of this frame stays above the BPSK and 1/2 coding rate reception threshold throughout this period, the PHY moves into the RXing state to stay for the frame duration. If a later arriving frame from the channel has sufficient received signal strength to prevent proper preamble and PLCP header reception for the current frame, the PHY moves back to the Searching state. However, if this later frame has sufficiently higher signal strength for its own preamble to be heard above others, it will, if activated, trigger preamble capture, which means the PHY stays in the PreRXing state with a reset timer for the new frame.

Within the RXing state, the PHY handles the reception of the body of the current frame. It monitors the SINR throughout the frame body duration. If the SINR drops below the threshold required by the modulation and coding rate used for the frame body at any time while in this state, the PHY marks the frame with an error flag. After RXing timeout, the PHY moves back to the Searching state. It also passes the frame to the MAC, where the error flag is directly used for the CRC check decision.

If the payload capture feature is enabled, then it is possible for a later arriving frame to trigger the PHY to move back to the PreRXing state for the new frame in the manner described in Section 5.3.4. Otherwise, the later arriving frame has no chance of being received and is only tracked by the power monitor as an interference source.

A transmit command from the MAC will move the PHY into the TXing state for the duration of a frame transmission regardless what the PHY is doing at the moment. The expiration of the transmission timer ends the TXing state. If a frame comes in from the channel when the PHY is in the TXing state, it is ignored and only tracked by the power monitor as interference.

Usually the MAC will not issue a transmit command while the PHY is in the PreRXing or RXing state because of the carrier sense mechanism. However, the IEEE 802.11 standard mandates the receiver of a unicast data frame addressed to itself to turn around after SIFS and transmit an ACK frame regardless of the channel condition. Similarly, the receiver of a RTS frame, if it has an empty network allocation vector (NAV), will wait for SIFS and then transmit a CTS frame regardless of the channel condition. The PHY is designed to drop and clean up the frame it is attempting to receive and move into TXing state when this happens.

5.5.3 Medium access control layer MAC model

As shown in Figure 5.4, there are six modules defined within the MAC. These six are 1) transmission, 2) reception, 3) channel state manager, 4) backoff manager, 5) transmission coordination and 6) reception coordination. The solid lines in the figure show the paths for passing data and control frames while the dashed lines indicate active signaling interfaces among the modules. The design of these six modules reflects considerations and abstractions of the extensive state diagrams contained in the IEEE 802.11 standard. However, not all decisions made in this work conform to the design in the standard. For example, the reception module in this design is simplified and some of the responsibilities (e.g. duplicate frame removal) are moved over to the reception coordination module instead.

Transmission module: The transmission module is the interface to the PHY. It passes all types of frames to the PHY for actual transmissions. The transmission module accepts RTS and data frames from the transmission coordination module, and ACK and CTS frames from the reception coordination module. When upper MAC management features (e.g. associations) are incorporated, it will also accept management frames from the new modules. The transmission module has a very simple state machine, which consists of only two states: TX_IDLE and TXing.

Reception module: The reception module completes the reception process of an incoming frame, which is started at the PHY. It applies address filtering on successfully received frames before passing them to other modules. It is also responsible to signal to the channel state manager with virtual carrier sense updates. As a frame comes up from the PHY, the reception module performs a CRC check to see if the frame is successfully received. It does so by consulting the value of the error flag, which is set by the PHY, attached to the frame.

The standard requires a node that just received a bad or unknown frame to wait for an extended inter frame space (EIFS) instead of the standard DIFS. The inter-frame spacing is treated in this design as the responsibility of the channel state manager. Therefore, the reception module informs the channel state manager in cases of CRC check error. The reception module applies address filtering on all successfully received frames, and only passes a frame to the appropriate recipient module if the frame is intended for this node. When BSS or IBSS support is added in the future, the BSSID filtering process should be placed in this module. For now, the reception module only passes data and control frames to the reception coordination module. When upper MAC layer features are added, the reception module should pass management frames to the new modules as appropriate. Any frame that does not pass the address filtering process is examined to see if it contains a NAV before been discarded. RTS, CTS and sometimes data frames contain NAV information. If one is found, the reception module passes the NAV value to the channel state manager. The reception module also has a simple state machine. It is in either RX_IDLE or RXing at any time.

Channel state manager: The channel state manager is responsible for maintaining both the physical and virtual carrier sense statuses for the IEEE 802.11 CSMA/CA mechanism. The channel state manager depends on the PHY to update the physical carrier sense status. It expects the PHY to signal channel busy when the total received signal strength rises above carrier sense threshold or when the PHY is in transmission. Similarly, it expects the PHY to signal channel clear when both conditions are gone. The channel state manager expects signaling from the reception module for virtual carrier sense status updates as described in the above subsection. Once signaled this way, the channel state manager sets or updates the NAV for the duration specified.

The channel state manager has five states. The combination of both physical and virtual carrier sense statuses result in four states: NoCSnoNAV, NoCSNAV, CSnoNAV and CSNAV. Additionally, the time spent in inter frame space (IFS) waiting is also modeled as a state within the channel state manager. This is because the IFS mechanism is essentially a self enforced NAV. As such, the channel state manager treats the Wait IFS state as channel being busy as well.The duration of IFS waiting time depends on the ifs_value parameter, which can be set to DIFS and EIFS. When EDCA is incorporated, it will be necessary to add an additional signaling interface from the transmission coordination module to the channel state manager to advise the AIFS values. SIFS waiting, however, is handled by the transmission and reception coordination modules directly. This is because SIFS is used in a way unlike that of DIFS and EIFS. Any module that sets a SIFS timer will take action as the timer expires regardless of the channel condition during the SIFS.

The channel state manager reports the joint physical and virtual carrier sense status in response to queries from any other module. That is: it reports CS_IDLE if it is in the NoCSnoNAV state, and CS_BUSY otherwise. It also reports the NAV status to the reception coordination module when queried, to assist the CTS decision. The channel state manager actively signals the backoff manger whenever it moves in or out of the NoCSnoNAV state to indicate channel status changes. In turn the backoff manager resumes or pauses its backoff process if it is already in one.

Backoff manager: The backoff manager maintains the backoff counter to support the collision avoidance mechanism in the IEEE 802.11 MAC. The backoff manager assists the transmission coordination module to run both the regular backoff and post-transmission backoff, but is not aware of the difference between the two. The backoff manager has three states: No Backoff, Backoff Running, and Backoff Pause. It depends on the signaling of channel carrier sense state from the channel state manger to run or pause the backoff counter. It moves back to the No Backoff state and signals Backoff Done to the transmission coordination module when the backoff counter reaches zero. When EDCA is added, it will be necessary for an additional signaling interface to be implemented between the transmission coordination module and the backoff manager to trigger a reassessment of the backoff process with a different contention window (CW) value. In turn, it could cause the ending of the backoff sooner in cases of higher priority pending frames.

Transmission coordination module: The transmission coordination module manages channel access for packets passed down from the upper layer. It is roughly divided into two sides depending on whether the RTS/CTS exchange is needed. If the data frame is a broadcast or a unicast with size less than the RTS threshold, it is entirely processed within the right side of the overall state machine. Otherwise, a RTS frame is generated and a sequence of states on the left side is involved before the data frame would be sent.

When the transmission coordination module moves out of the TXC_IDLE state because of a packet coming down from the upper layer, it first checks if a RTS frame should be generated. Afterwards, it starts a backoff process at the backoff manager if there is not one going on already and moves into the RTS Pending or Data Pending state according to the RTS decision. If the transmission coordination module is in the RTS Pending or Data Pending state, it instructs the transmission module to transmit the RTS or data frame respectively as soon as receiving a signal indicating Backoff Done from the backoff manager. It is possible for these pending states to be directly bypassed. If the backoff manager does not have a backoff process currently going on and the channel state manager replies with a CS_IDLE, the transmission coordination module can immediately transmit the RTS or data frame. This is because the standard allows for a radio to start a transmission right away if it has completed a previous post-transmission backoff and the channel, both physically and virtually, has been idle for more than DIFS. When the transmission of a RTS frame is completed, the transmission coordination module moves into the Wait CTS state and starts a timer TCTS. If the reception coordination module does not signal the arrival of a CTS frame before the timer expires, it starts another backoff process and moves back to the RTS pending state. It can repeat this process until the short retry limit is reached. If a CTS response comes back in time, then the transmission coordination module waits for SIFS before instructing the transmission module to send the data frame.

After data frame transmission, the transmission coordination module moves into the Wait ACK state and starts a TACK timer. If it does not get an ACK reply indication from the reception coordination module before the timer expires, it starts a new backoff process and moves back to RTS Pending or Data Pending state respectively. Again, this is subject to the short or long retry limit respectively. In cases of RTS retry or unicast retransmission, the contention window parameter is updated before a backoff is requested with the new value.

The attempted transmission of a frame finishes in three possible ways: 1) it is a broadcast frame and it is transmitted once over the air; 2) it is a unicast frame and the transmission coordination module receives an ACK signaling from the reception coordination module; or 3) one of the retry limits is reached. In all three cases, the transmission coordination module resets the retry counters and the contention window parameter, and starts a post-transmission backoff. Afterwards, if there is a packet waiting in the queue, it takes the packet and immediately moves into the RTS Pending or Data Pending state. Otherwise it returns back to the TXC_IDLE state.

Reception coordination module: The reception coordination module takes the control and data frames meant for this node from the reception module. It signals the transmission coordination module when CTS and ACK frames arrive. It is responsible to handle the CTS and ACK responses when RTS and data frames arrive. It also filters the data frames before passing them to the upper layer. The reception coordination module has only three states: RXC_IDLE, RXC SIFS Wait, and Wait TX Done. The reception coordination module mostly spends time in the RXC_IDLE state and awaits control and data frames from the reception module. If a RTS frame arrives, the reception coordination module queries the channel state manager for its NAV status. If the response indicates an active NAV, the RTS frame is simply discarded. Otherwise, the reception coordination module creates a CTS frame and moves into the RXC SIFS Wait state with a SIFS timer set. When the timer expires, it immediately instructs the transmission module to transmit the CTS frame. It then moves into the Wait TX Done state for the transmission duration before returning to the TXC_IDLE state.

If a unicast data frame arrives, the reception coordination module starts an ACK process similar to the way it handles the CTS response. However, it does not consult the channel state manager for the NAV status. If a CTS or ACK frame arrives, the reception coordination module simply signals the transmission coordination module accordingly. The reception coordination module passes data frames to the upper layer. In this process, it is responsible to discard duplicate data frames coming in from the channel, which can be caused by the unicast retransmission mechanism. In these cases, however, it still reacts with an ACK transmission.

5.5.4 Summary

In this chapter, we presented a clean and modular architecture for IEEE 802.11 simulations in NS-2. The roles, functions and signaling interfaces of all major modules in the MAC and PHY are described systematically. In terms of modeling accuracy, we showed an important step towards modeling the IEEE 802.11 transmissions and receptions process realistically and correctly. The addition of probabilistic propagation models, cumulative SINR, preamble and PLCP header handling and capture, and frame body capture features to the PHY improves simulation accuracy and provides more insights and more detailed simulations. The implementation of the models became an integral part of the distribution of NS-2 from version 2.33 onwards, see [NS-2], and is thus provided to the research community and intensively used. Further information on the modules and updated versions are provided on our project website [WWW NS-2Ext].

6

Simulation and assessment of vehicle-to-vehicle communication networks

In this chapter we assess the performance of V2V networks by means of simulations. As we discussed in Chapter 5, detailed simulation models are needed in order to accurately represent the properties of the different components of the communication system and the influences of the environment with an appropriate level of detail. The assessment by simulations covers a comprehensive amount of scenario configurations that possibly occur in reality in order to gain an insight on the performance that can be expected over a broad set of scenarios and parameters. As we will see in the subsequent sections, the space opened by the multiple effects to be modeled and the multitude of possible system parameters gives the possibility to analyze each instant combination of scenario setup and parameters. However, an individual analysis of each single combination of parameters is neither useful nor manageable. Although the necessary computations can be performed, what is the case for the scenario and parameter space presented in Section 6.1, analyzing each individual combination would not bring an overall understanding of what is being observed. Instead, we carry out an analysis as follows.

We first describe the simulation analysis process that we follow and the reasoning for the chosen methodology. The analysis presented in this chapter follows a three-phase strategy where, with each phase, the complexity of the analysis increases and the derived conclusions reach a more general message with respect to the overall system. In principal, we provide a fundamental factors analysis of the system models, followed by a sensitivity analysis of the system parameters, and conclude with a joint system capacity analysis that includes all aspects and respects requirements given by the applications. For all considerations, we base the studies on scenarios that inherit a specific number of vehicles per highway kilometer, i.e. all analysis is based on a set of scenarios where each of them is populated with a specific node density, and the nodes are positioned at random places over the highway.

Before the different analysis phases are described in the following we describe the simulation setup in Section 6.1. We introduce the variety of models and parameters and describe how the simulations were actually performed and evaluated. In Section 6.2 we specify all metrics that are used in the subsequent sections in order to evaluate the results and explain how simulations are evaluated. We distinguish three different types of evaluation that are applied in all phases of the evaluation. First, a major metric of fundamental interest in all considerations is the distance-dependent successful packet reception ratio. Second, a distance-based reception and failure categories analysis is developed and presented to allow a detailed analysis of the reasons of achieving specific reception probabilities and the impact of interferences on these results. Third, a set of performance metrics is defined that describe a complete scenario with respect to a specific aspect.

In *phase 1*, we perform a *fundamental factors analysis* where we consider the different possibilities of modeling the system components, thus, we consider the impact of the model selection. The focus of this phase is put on the fundamental differences how results look like, depending on the model chosen in the simulations. As we want to model reality as close as possible, we will concentrate on more realistic models and show the main differences to simplified models. First, we concentrate on the consequences of the usage of a specific radio propagation model in the simulations, i.e. on representing the effects that influence transmitted radio waves on the medium, caused by the environment. Second, we consider the details that are modeled with respect to the characteristics of the radio receiver, in particular its capture capabilities. Third, we discuss the choice of the modulation scheme and coding rate on the PHY layer what is strongly related to the maximum achievable bit rate of the system. Although this aspect could alternatively be treated as a communication parameter instead of a fundamental factor, in a communication network that mainly distributes broadcast messages the data rate used is a basic design decision. In difference to unicast transmissions where the data rate can be dynamically adapted to be sufficiently good for a distinct link between two nodes there is no such possibility for broadcast communication. Consequently, we include the selection of data rate that is commonly applied by all participating nodes in the fundamental factor analysis of phase 1.

In *phase 2*, we perform a *sensitivity analysis* in which we investigate the different parameters that the communication system offers, thus, we consider the impact of the parameter selection. In difference to phase 1, not the models themselves, but configurable parameters are tested and the consequence of their choice is analyzed. For these considerations, a huge selection of scenarios and parameter values is considered that represent the wide spectrum of possible implications. We discuss the consequences of different packet sizes as well as packet transmission rates of the applications, and the selection transmission power with which the packets are transmitted to the medium. The results are shown for selected scenarios in which the influence of each parameter can be analyzed independently from the other parameters. Thus, in the analysis of phase 2, we identify the overall trends that occur with the variation of each individual parameter. The sensitivity analysis is presented in Section 6.4.

Phase 1 identifies the implications of models for V2V simulation studies and phase 2 provides insights to the consequences of setting the configurable parameters of the system. The results gathered are useful and valuable in order to design and configure communication systems, but they still do not provide an answer to the questions raised in Section 2.3: how does a system have to be configured and designed such that the requirements are fulfilled that allow the application to work reliably? Further, is the communication system capable at all to fulfill the requirements? And, under which conditions do we reach a state where the requirements can not be provided anymore.

We discuss these question in *phase 3* of our considerations, the *system capacity analysis*. We consider all combinations of influencing factors and parameter settings to derive the achievable local broadcasts capacity that a system is able to provide for a scenario with specific node density. From the definition of local broadcasts capacity in Section 4.3 we observe that in order to calculate this metric, the data rate of the channel, the awareness range defined by the application and the required successful packet reception ratio within the awareness range are basic input parameters. Consequently, we provide the local broadcasts capacity with respect to this tuple of information and can relate and compare the results. In the next step, we include the consideration of constrained local broadcasts capacity where the achievable capacity is restricted by additional performance requirements defined by the application. The observations in this chapter provide general numbers on the intensity the communication system may be used. Thus, we provide an analysis that is useful to observe whether the performance requirements of the applications can be fulfilled. The system capacity analysis is presented in Section 6.5.

After the described analysis process we will in Section 6.6 on the one hand conclude the observations made and discuss the applicability, impact and relevance of the results. On the other hand, we give an overview where the described detailed simulation models have been applied and used by us and by other research groups in order to achieve further results. The strategy of performing intensive simulation studies was, among others, used to derive stochastical models of reception performance of V2V communication systems, and to identify the most promising data rate for V2V communication.

6.1 Configuration and setup

In this chapter we describe the configuration and setup for all simulation studies and we identify the factors and parameters that are studied. The road scenario layout taken for the evaluation represents different snapshots of vehicle positions on a 5.0 km long extract of a highway. The HWGui tool [WWW HWGui 2005] provides realistic node distribution and node movement patterns for several densities and traffic situations. However, we want to discuss the results over an even wider range of node densities than could be provided, and neither node movement nor precise node positions are a primary issue when considering single-hop broadcast transmissions; yet, these influences would be substantial when e.g. considering multi-hop forwarding of messages, what we actually do *not* do. Consequently, we created our own scenarios, covering the major features known from the HWGui tool, but abstracting from the ones not relevant for broadcast studies. We assume static nodes that are randomly distributed along a linear highway scenario with different defined densities, see Table 6.1 for the ten node densities investigated. For each density, several independent node placements were created and then used for the simulations. For all evaluation effort presented later, we restricted the evaluation to the nodes being positioned within the inner 3.0 km of the scenario, i.e. skipping all statistics contributed by nodes positioned closer than 1.0 km to the scenario border to avoid any border effects.

Parameter	Unit	Configurations
Vehicle density d	nodes/km	20, 40, 60, 80, 100, 120, 140, 160, 180, 200

Table 6.1: Node densities used in the simulation studies

Each node of a scenario is equipped with an application agent that periodically generates messages that are given down the stack to the communication layers to finally being transmitted. The *periodic broadcast agent* is configured with respect to the packet size and the packet transmission rate, thus, in each simulation run, *all* nodes are identically configured and generate the same amount of data. The duration of the interval between the generation of two subsequent message is given by the packet transmission rate. A jitter of 10 % of the duration of the interval is included, thus, each time the duration varies within ± 10 %. If new messages are generated while previously generated messages were still not transmitted, the new messages are stored in an interface queue that is capable to store up to 10 packets at maximum.

The communication stack is configured with respect to the parameters defined in the standard draft of IEEE 802.11p [802.11p 2009] that was described in Section 2.4.2. In Table 6.2 the constant configuration parameters are listed and will now be shortly explained.

Layer	Parameter	Value
MAC	Slot time	13 μs
	SIFS time	32 μs
PHY	Carrier frequency	5.890 GHz
	Channel bandwidth	10 MHz
	Preamble length	32 μs
	PLCP header length	8 μs
	OFDM symbol duration	8 μs
	Carrier sense threshold CSTh	-94 dBm
	Noise floor	-99 dBm
	SINR threshold for preamble capture	5 dB
	SINR threshold for frame body capture	10 dB
Antenna	Antenna height	1.5 m
	Antenna gain	0.0 dBm

Table 6.2: MAC and PHY configuration parameters used in the simulation study.

With respect to the physical layer, the central frequency of the carrier channel used for transmissions is set to 5.890 GHz, what is the channel proposed for the common control channel (CCH) in both American and European standardization, see Section 2.4.2. The carrier frequency influences the extent of the large-scale path loss. The channel bandwidth is set to 10 MHz, as proposed for IEEE 802.11p. It determines the bandwidth of each sub-carrier and subsequently the duration of a single OFDM symbol, being 8 μs long. The IEEE 802.11p standard further defines the header duration being as long as a symbol duration and containing necessary information for the reception of packets. Previous to the header, each packet includes a preamble for the overall duration of 32 µs, in which training symbols are transmitted in order to identify the beginning of a packet and to adjust, train and initialize the receiver units in the network interfaces. We refer to Section 2.4.2 for further discussion of physical layer issues.

The noise floor describes the power level of the sum of all noise power. The noise power consists of thermal noise as well as losses in the receiver hardware, e.g. in the antenna cables or the noise caused by electronic parts. The selected value serves as an average value for all such effects and is assumed constant at -99 dBm during the whole simulation. The carrier sense threshold for busy/idle notification to the MAC is set to -94 dBm in our studies although the standard document defines a higher value of -85 dBm. A higher value leads to a more aggressive usage of the communication channel as the channel is determined idle with higher probability. In the broadcast scenario we consider, however, interferences caused by multiple nodes trying to access the channel strongly affects the reception probability, as we will see in the study. In order to mitigate these effects, reducing the carrier sense threshold to a level where packets can already be successfully received is one strategy. Yet, the detailed analysis of the effects are not within the scope of this thesis.

The threshold values for preamble/header as well as payload capture are technology and manufacturer-dependent and define the level of power increase that leads to the activation of the capture capabilities. The values used are the result of private conversations with chipset manufacturers and provide a trade-off at which level of reception power a capture is a useful strategy to be applied. Here, we set the threshold during preamble/header reception of another frame to 5 dB, corresponding to the SINR that has to be achieved in order to initially distinguish a packet reception from noise. During payload reception, a higher power increase of 10 dB is taken as an indication to switch to the newly arriving frame. As we will see in Section 6.3.3 the capture capability is an important factor to improve successful reception from nodes positioned closed by.

The MAC layer is configured with respect to values defined in the standard [802.11 2007, p. 626]. The slot time determines the length of a backoff slot during medium access and defines the durations of the IFSs. The SIFS is the basic duration that also defines all other IFS durations.

As described, the evaluation is performed with respect to the influence of several fundamental factors first. In Table 6.3 the three different factors discussed, i.e. propagation model ,capture capability, and data rate are shown. The variants that are discussed in the evaluation and the abbreviations that are used in the plots and descriptions are listed. From the table, we see that a basic variation of three propa-

Parameter	Abbreviation	Configuration
Propagation models	Two Ray Ground	Two Ray Ground (no fading)
	Nakagami-1	Rayleigh fading (Nakagami-m, m=1)
	Nakagami-3	Nakagami-m, m=3
Capture capability	Cap_Off	Capture disabled
	Cap_Pre	Capture during preamble and header reception
	Cap_Full	Capture during preamble, header and payload reception
Data rate, modulation scheme and coding rate	3 Mbps	3 Mbps, 1/2 coding rate, BPSK modulation
	6 Mbps	6 Mbps, 1/2 coding rate, QPSK modulation

Table 6.3: Fundamental factors analyzed in the simulation study

gation models, three different options of capture capability and two different data rates are discussed, what leads to 18 basic system variations that are analyzed. The listed propagation models are taken to have a comparison between deterministic propagation behavior and different intensities of small-scale fading. The different levels of capture capability will show the impact that receivers that support capture can provide. With respect to data rates, the most robust scheme that also provides the lowest data rate (3 Mbps) is compared with the scheme that was identified to perform optimal in a wide range of scenarios (6 Mbps), see [Jiang et al. 2008]. Some of the results shown in the figures only include results with a rate of 3 Mbps in order to achieve the performance in the worst case with respect to data rate.

In the subsequent sensitivity analysis, we explore a wide field of configuration parameters that are listed in Table 6.4. The table shows the broad spectrum each configuration parameter is varied in reasonable ranges. The packet sizes vary from small packet of 100 byte up to packets being large for periodic messages (1,000 byte). The message generation rate is varied from 2 to 14 packets per second, with respect to expected required update of application. Transmission power is varied within the range allowed by regulation. Currently, the two lowest transmission powers can technically not be configured in real systems but give an impression of the results to be expected. Transmission powers are coupled to the intended transmission distance, that gives the distance that can be successfully reached under the assumption of a deterministic Two Ray Ground radio propagation model, and without any disturbances from interferences. Note that the range provided thus only is a number that supports the readability, but does not reflect real ranges, as we will see in the results observed. All simulations are run for three different configurations for the contention window, as it has to be adapted in case of intensive broadcast traffic. Overall, we analyze 2,100 different parameter configurations.

Parameter	Unit	Configurations
Message size s	byte	100, 200, 300, 400, 500, 600, 700, 800, 900, 1000
Message generation rate f	s^{-1}	2, 4, 6, 8, 10, 12, 14
Transmission power P_t	dBm	-6.16, -0.14, 3.39, 5.89, 7.82, 10.08, 12.76, 15.08, 17.13, 18.96
Corresponding intended transmission distance m	m	100, 200, 300, 400, 500, 600, 700, 800, 900, 1000
Contention window		7, 31, 127

Table 6.4: Parameter configurations simulated for each combination of fundamental factors

Summing up, we achieve a considerable number of combinations of vehicle densities, fundamental factors and configuration parameters that are simulated within the study. Actually, 10 densities multiplied by 18 fundamental factors variations and by 2,100 configuration parameters leads to an overall number of 378,000 simulated scenarios. Each scenario is run for 10 seconds, the first second being skipped from evaluation to exclude the start-up phase and achieve results in steady state. In order to achieve significant results, the scenarios have to be simulated for various seeds. The number of seeds was chosen individually from 2 to 10, depending on the "importance" of the according scenario; some combinations are given more attention are run for a higher number of seeds, and some less important ones are are only simulated for two seeds, in order to save some computation power. In order to guarantee confidence, the 95 % confidence interval is determined for for each individual data point. The plots contain the confidence intervals, although some of them are not visible being too small. Exploring the data, we observe reasonable confidence in the values achieved.

The huge amount of simulated scenarios allows to identify the trends that appear when varying the mentioned factors and parameters. We will show a representative selection of results in the following sections as all available data cannot be presented due to the enormous amount.

The simulations were performed on the HP XC 4000 high performance cluster of the Steinbuch Centre for Computing (SCC) at the Karlsruhe Institute of

Technology (KIT). The cluster has an overall performance of 15.77 TFLOP/s and 12 TB main memory capacity. It, apart from two nodes differently configured, consists of 750 four-way computing nodes, each equipped with 2 AMD Opteron Dual Cores (HP ProLiant DL145 G2) running at a clock speed of 2.6 GHz and equipped with 16 GB of main memory and 144 GB local hard disk storage. Each node provides a peak performance of 20.8 GFLOP/s. Adding up all the processing time that was used on the high performance cluster, the simulation study presented in the following took 8,200 days of computing time if translated to sequel computation and on a single core. The considerable amount of simulation time needed gives an impression on the dimension of the computational effort required that is only achievable in an acceptable amount of real time when making use of high performance computing resources. More details on using high performance computing for V2X communication studies is provided in our publication [Jetter et al. 2009].

6.2 Evaluation metrics

In this section we will specify the metrics that are used to evaluate each configuration of a simulation. We provide a definition of each metric, followed by a short description of its application. All metrics only refer to the statistics gathered by nodes in the inner region of the scenario in order to avoid border effects; all nodes being closer than one kilometer to the scenario border are not considered. Also, the first second of each simulation is not taken into account to exclude the warm-up period.

6.2.1 Performance metrics

Packet generation rate (PGR): The average number of packets that a node generates per second in order to transmit the packets as a broadcast to the wireless medium. The packet generation rate (PGR) accounts for all packets generated by the application. The PGR is related to the scenario specific configuration, where packet generation frequency is one configuration parameter. As the generation of packets is jittered, the configuration parameter and the metric behave similar, but may not be identical.

Packet transmission rate (PTR): The average number of packets that a node physically transmits per second on its network interface to the wireless medium. The packet transmission rate (PTR) considers only the packets that passed the MAC procedure and are actually put on the medium. PTR allows to observe the effective packet rate a node is capable to provide under the conditions given.

Packet transmission ratio (PTRo): The ratio of number of packets that a node transmits and the number of packets that a node generates. The ratio is calculated by dividing PTR through PGR. The packet transmission ratio (PTRo) allows to observe the capability of a node to fulfill the request given by its configuration. If PTRo is low, many generated packets have to be discarded as the overall situation does not allow to transmit all of them, e.g. due to a saturated channel. If PTRo is 1.0, the configured transmission performance can be provided.

Channel access time (CAT): The average amount of time in seconds that a packet is processed or queued in the node from the moment of its generation (and wish to be transmitted) until it is put on the wireless channel. The calculation of channel access time (CAT) only includes messages that finally access the channel; discarded packets are not taken into consideration. CAT covers *i)* the time that a packet spends waiting in the interface queue in case that the MAC layer is still occupied by the processing of a preceding packet and, *ii)* the time that a packet spends waiting in the MAC layer before being granted to access the wireless channel. The latter period of time is the delay caused by the DCF or EDCA MAC method. Note that if the CAT observed exceeds average time between two packet generations, i.e. PGR^{-1}, CAT sums up due to the queue in the node that fills up to maximum and will never be emptied again during the rest of the simulation. Thus, if such situation occurs, the measured CAT is not a meaningful measure anymore. Still, for all other cases it delivers meaningful results. In the study we will present the values under all conditions, putting the ones not meaningful in italics.

Channel busy time (CBT): The ratio of time for which MAC considers the medium busy. The medium is considered busy whenever either *i)* the measured cumulative power a node observes exceeds the CSTh, or *ii)* a node locked on the reception of a frame, i.e. it successfully detected a preamble and header of a frame, or *iii)* a node actively transmits a packet to the wireless medium. Otherwise the medium is considered idle. The channel busy time (CBT) represents the intensity the medium is occupied. A high CBT typically causes higher CAT.

Successful packet reception rate (SRR): The average number of packets that a node successfully receives per second from another node in the scenario. successful packet reception rate (SRR) considers each packet that successfully passes the PHY procedures and is considered being received successful. The SRR allows to derive the amount of packets per second that a node can provide to the applications in order to further process the contained data. In contrast to the metrics described before, SRR is presented with respect to the distance that a packet travelled from transmitter to receiver. Specifically, each packet being successfully received at a node is assigned to a distance bin, depending on the distance from node that transmitted the packet to the receiving node. Each transmitted packet is considered as being either received or not received successfully by each other node in the scenario.

Successful packet reception ratio (SRRo): The ratio of the number of packets that a node receives from a distinct different node and the number of packets that the distinct node in the scenario actually transmits. As SRR, Successful packet reception ratio (SRRo) is provided with respect to the distance that a packet travelled from transmitter to receiver. The ratio is calculated by dividing for each distance bin PTR and SRR of the corresponding nodes, i.e. all node combinations that fall in the particular distance bin. SRRo represents the reliability of the packet transmission process with respect to the distance between the nodes. SRRo is the major metric also used in the definition of local broadcasts capacity. SRRo is synonymously called "*probability of successful packet reception*".

Thus, we identify metrics of different type: while PGR, PTR and PTRo deliver information on the transmission behavior of nodes with respect to the amount of packet processed, CAT delivers information on the transmission behavior with respect to time. Considering the usage of the transmission medium, CBT provides information on the intensity with which the medium is used. The reception of packets is considered by the metric SRR with respect to the absolute amount of packets received. SRRo considers both, transmission and reception behavior and relates them to each other, thus, provides information on the reliability of communication between nodes with respect to the distance.

6.2.2 Interference analysis: reception and failure categories

The understanding of the influence of different types of interferences as well as the influence of the capture capabilities of a receiver is supported by a detailed analysis of the incoming packets. The packet reception categories described in the following provide such a possibility. Here, the advantage of an evaluation by simulations can be prominently shown: it is possible to not only consider successfully received packets, but it is also possible to analyze the reasons why a specific packet was not successfully received.

Table 6.5 gives an overview of the different reception and failure categories. The basic concepts of the categories ant the evaluation method were introduced and presented in [Torrent-Moreno et al. 2006] and [Schmidt-Eisenlohr et al. 2007]. Since then, the categories were further extended and refined to adapt to the needs of the analysis. The different categories are defined and described in the following. Each packet that a node might possibly receive is analyzed and, depending on the reception situation at the receiving node during the time between the start and the end of the packet reception, the packet is assigned to exactly one of the categories.

Reception status	Category	Description
SUCCESS	SUC	Successful reception without interference
	SUC-INTF	Successful reception with interference
	SUC-CAP	Successful reception due to capture
FAILED	FAIL-PROP	Packet lost due to radio propagation
	FAIL-MAC	Collision due to parallel medium access of several nodes
	FAIL-TX	Packet not receivable due to own transmission
	FAIL-CAP-PRICE	Collision due to capture of other packet
	FAIL-CAP-MISS	Collision of candidate for capture, but not activated

Table 6.5: Reception and failure categories.

Successful reception without interferences (SUC): A packet that was successfully received, the start of the reception was possible without using any capture mechanism, and during the reception interferences from other nodes were not recognized. The latter condition means that not even a packet with low reception power that interferes the other reception was sensed at the node during the reception period[1].

Successful reception with interference (SUC-INTF): A packet that was successfully received, the start of the reception was possible without using any capture mechanism, but during the reception other packets were recognized and interfered. Still, the successful reception was possible as the SINR always remained high enough during the reception period.

Successful reception with capture (SUC-CAP): A packet that was successfully received, the start of the reception was enabled by using the capture capability during the reception process of another packet that was not received successfully in consequence. If capture capabilities are disabled, no packet can fall in this category. If preamble/header capture was activated, the other packet was in preamble or header reception phase when capture was applied. If full capture was

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[1] Note that packets with reception power below CSTh are not considered as interferers in the SUC and SUC-INTF metric. In the simulation itself, however, such packets are fully considered. Thus, the case that multiple packets of very low reception power in sum cause interference is considered.

activated, the other packet was in preamble/header or payload reception phase. During the reception period of the captured packet interference by other packets surely happened as well; at least the packet that was stopped being received due to the capture mechanism actually is an interferer at least during the start of the reception. The reason for the successful reception is the availability of the capture capability at the receiver.

Packet lost due to radio propagation (FAIL-PROP): A packet that failed to be received and its reception power was too weak to be successfully received even in the absence of any interferences. The required SNR was not achieved either during preamble and header reception or during payload reception. During payload reception the required SNR can be different depending on the coding rate and modulation scheme used at the transmitter. The FAIL-PROP category preempts the other categories for failed packets; packets that would match for another category as well are assigned to the FAIL-PROP category. The reason for reception failure are the characteristics of radio propagation, large-scale path loss and small-scale fading effects.

Collision due to parallel medium access of several nodes (FAIL-MAC): A packet that failed to be received although its reception power would have been high enough to be successfully received in the absence of interferences. Yet, due to multi-user interferences caused by other timely overlapping packets the required SINR was not achieved at least once during the packet reception. The reason for reception failure are multi-user interferences, caused by a MAC process that was not capable to avoid collision of several packets or by transmissions from hidden nodes. No other packet was able to benefit from the reception failure, e.g. by being received due to the capture feature. In that case the packet would have been be assigned to the category FAIL-CAP-MISS.

Packet not receivable due to own transmission (FAIL-TX): A packet that failed to be received because the node was transmitting a packet itself at the moment of the arrival.

Collision due to capture of other packet (FAIL-CAP-PRICE): A packet that failed to be received although its reception power would have been high enough to be successfully received in the absence of interferences. Yet, another packet that arrived during the reception had strong enough reception power to fulfill the criterion for a capture, either during the preamble/header reception, or during payload reception of the packet. The reason for reception failure is the capture capability of the receiver, yet with an advantage for another packet. Packets in the FAIL-CAP-PRICE category are “the price that has to be paid” to achieve an advantage of the capture capability. If capture capabilities are disabled, no packet can fall in this category.

Collision of candidate for capture, but not activated (FAIL-CAP-MISS): A packet that failed to be received although its reception power would have been high enough to be successfully received in the absence of interferences. The start of the reception would have been possible by using the capture capability during the reception process of another packet, but capture capabilities were disabled. The reason for reception failure is the non-availability of capture capability of the receiver that would possibly have allowed the successful reception of the packet. Packets in the FAIL-CAP-MISS category are "the chance that was missed" due to missing of according receiver capability, or in other words, the potential that the support of capture could have provided. If capture capabilities are enabled, no packet fall in this category.

The different reception and failure categories allow to identify which factor is responsible for a good or a bad performance with respect to packet reception. In the next sections, the analysis of the reception and failure categories is provided with respect to the distance between transmitter and receiver. For every distance the ratio that the packets in each category achieve in comparison to all packets registered and categorized is shown. In consequence, the SRRo metric defined in the last Section 6.2.1 is the sum of all ratios achieved by the categories leading to a successful packet reception, thus, categories that begin with "SUC-".

6.3 Fundamental factors analysis

In the following, we discuss the first phase of the analysis with respect to the fundamental influencing factors of the modeling of a system in simulations. We therefore compare the influence of different propagation models, of the capture capability and of the coding rate and modulation scheme, as it is shown in Table 6.3, and will observe the basic differences in communication performance.

6.3.1 Propagation models

We first investigate the behavior of different radio propagation models on the reception characteristics. First, we consider the situation for a single transmitter, thus, the reception characteristics purely caused by the propagation model, without interfering effects from other transmissions. Figure 6.1 shows the Successful packet reception ratio (SRRo) over distance between the single transmitter and several receiving nodes for the three different models under consideration, Two Ray Ground, Nakagami-1 and Nakagami-3. All packets are sent with the same transmission power of 3.39 dBm that corresponds to a maximum distance of 300 m for the deterministic Two Ray Ground model.

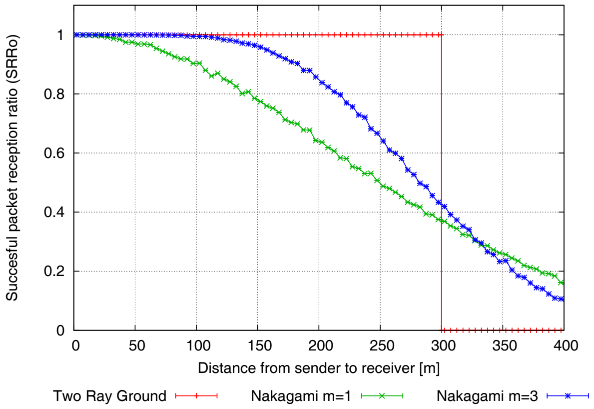
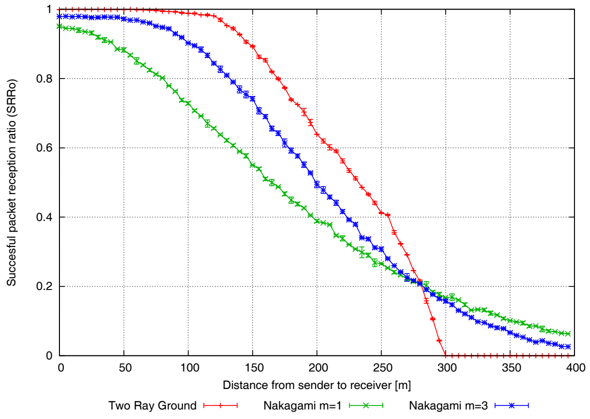


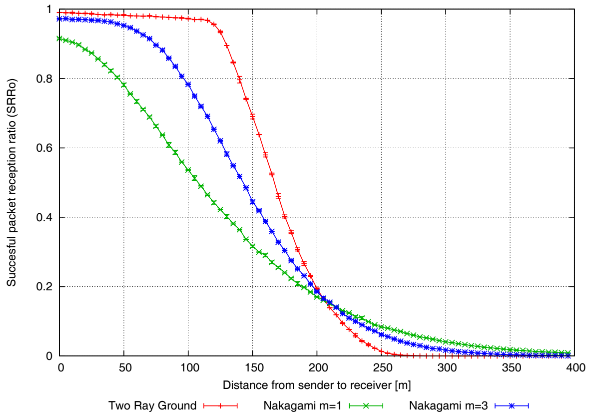
Figure 6.1: Successful packet reception ratio with respect to distance between transmitter and receiver without interferences from other nodes. The transmission power of 3.39 dBm corresponds to an intended communication range of 300 m under the deterministic Two Ray Ground model.

We observe that Two Ray Ground shows its deterministic behavior, up to a specific distance of 300 m all packets can be received, beyond that distance, packets cannot be received at all. The model shows a sharp decrease in SRRo at one distance, that we refer to as (deterministic) intended communication range. The two Nakagami-m models show a probabilistic reception behavior over distance: due to the fading effects on the signal amplitudes that are modeled as a Nakagami-m distribution, the reception power varies with a Gamma distribution, with the average reception power value as input parameter, see Section 3.1.3. In our simulations, no correlation of the channel is assumed, and reception power values are drawn independently from probability distributions defined per packet and per receiving node. We observe that the decrease of SRRo for the Nakagami-1 model is more severe and starts at closer distances, caused by the fact that the model represent severe fading conditions. The result observed for Nakagami-3 remains at high rates for a further distances, but then decreases with more intensity than Nakagami-1. It is important to observe that for the Nakagami-m models there is no fix distance at which the reception ratio instantaneously drops. There is still some probability that a reception is successful at distances where for Two Ray Ground no reception is possible anymore.

We now consider the regular case, thus, the situation where all nodes intend to transmit broadcast packets. In Figure 6.2 the three propagation models are compared for the case that all nodes in the scenario generate packets, i.e. all nodes request access to the wireless medium. Packets are sent with 1/2 coding rate and BPSK modulation, thus, with a rate of 3 Mbps. The packets have a size of 500 byte, a transmission power of 3.39 dBm is taken, corresponding to an intended distance



(a) 60 vehicles/km



(b) 140 vehicles/km

Figure 6.2: Successful packet reception ratio for different propagation models and node densities. Packets of size 500 bytes are transmitted with a transmission power of 3.39 dBm, every node generates 6 packets per second, the contention window is set to 127, capture capability are disabled and a data rate of 3 Mbps is used.

of 300 m, the packet generation frequency is set to 6 packets per second and the contention window is 127 to reduce the probability of selecting the same backoff slot for different transmissions. In Figure 6.2(a), the SRRo for a vehicle density of 60 nodes/km is shown, while Figure 6.2(b) shows the same configuration, but for 140 vehicles/km. The metrics with respect to transmission and channel are shown in the Tables 6.6 and 6.7.

We observe that with the Two Ray Ground model the probability of packet reception remains on a high level up to 130 m, the distance safe against hidden nodes. Then, the probability decreases due to the increasing impact of packet collisions caused by transmissions from hidden nodes that are not suppressed by a transmission. The effect is stronger in case of a scenario with higher node

Metric	Unit	Two Ray Ground	Nakagami-1	Nakagami-3
PGR	1/s	6.00	6.00	6.00
PTR	1/s	6.00	6.00	6.00
PTRo		1.00	1.00	1.00
CAT	ms	1.02	0.79	0.97
CBT		0.39	0.33	0.37

Table 6.6: Metrics of curves in Figure 6.2(a) (node density 60 vehicles/km)

Metric	Unit	Two Ray Ground	Nakagami-1	Nakagami-3
PGR	1/s	6.00	6.00	6.00
PTR	1/s	6.00	6.00	6.00
PTRo		1.00	1.00	1.00
CAT	ms	8.63	3.59	5.56
CBT		0.85	0.69	0.78

Table 6.7: Metrics of curves in Figure 6.2(b) (node density 140 vehicles/km)

density, thus, where more potential hidden nodes can be observed. As expected, no packets are received at any distance further than 300 m from its transmitter.

Both Nakagami-m models still show a smooth slope as in the case of a single transmitter but curves begin to decrease significantly earlier for both densities. In case of high node density we observe a stronger decrease of probability of packet reception. The reason for the stronger impact on reception probability compared to the deterministic model lies in the observation that with probabilistic radio propagation hidden nodes can be observed in closer distance from a transmitter of a message due to signal fades that may lead to not noticing a transmission and thus causing the transmission of a message in closer distance, leading to a collision. It can be observed that the influence of collisions caused by a MAC behavior not being able to avoid collisions already influence the reception behavior in very close distances to the transmitter, what can be seen by the considerable offset of the SRRo curve to the ideally reachable 100 % . The effect is more significant for Nakagami-1 fading, thus more intense fading, where the variations of reception power are much more present and influence the MAC schemes more severe.

Comparing the metrics of both node densities, we observe that the scenarios are selected such that all generated packets can actually be transmitted, see the PTRo metric in Tables 6.6 and 6.7. Yet, we observe that for the dense scenario we achieve a small increase of CAT and CBT. The observation is obvious as more nodes actually want to use the communication channel. The node density more than doubles, and CBT increases by a similar factor. Yet, the CAT increases with a higher factor, what can be explained by investigating the MAC process: with DCF (as well as EDCA) a backoff process is initialized whenever the channel is considered busy. At the moment the channel becomes busy, the process is paused, and it is continued when the medium is idle again for a duration of DIFS. Thus, each interruption of the backoff process adds an additional duration of DIFS to the CAT, and this can happen multiple times for each transmission. The probability for multiple interruptions increases with a more intense use and with a higher CBT.

We observe with respect to radio propagation models that the different slopes of the models lead to different SRRos even without any interferences. Further, in case that there are interferences, the different slopes influence the MAC scheme considerably. The effects are more intense when the node density is higher and when a more severe fading model is used. We further see that fading has fundamental influence on achieved reception ratios.

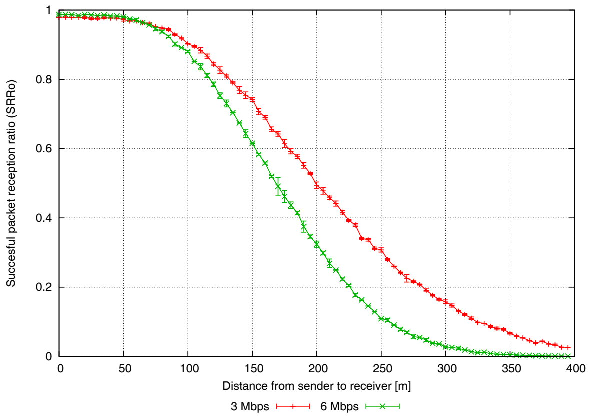
6.3.2 Data rate and modulation scheme

The selection of a coding rate and modulation scheme, and consequently the bit rate with which the packets are transmitted over the medium is discussed in this section. We therefore compare the two configurations mentioned in Table 6.3. With 1/2 coding rate and BPSK a data bit rate of 3 Mbps is achieved on a 10 MHz wide IEEE 802.11p channel, and for a successful reception an SINR of 5 dB has to be achieved in our simulation model, as described in Section 5.5.1. In contrast, with 1/2 coding rate and quadrature phase shift keying (QPSK) modulation a data bit rate of 6 Mbps is achieved, but a SINR of 8 dB has to be achieved for successful reception. Thus, it is not obvious which scheme provides better performance for broadcast communication. An optimization and adaption of the transmission scheme cannot be performed with respect to the quality of one link between two nodes.

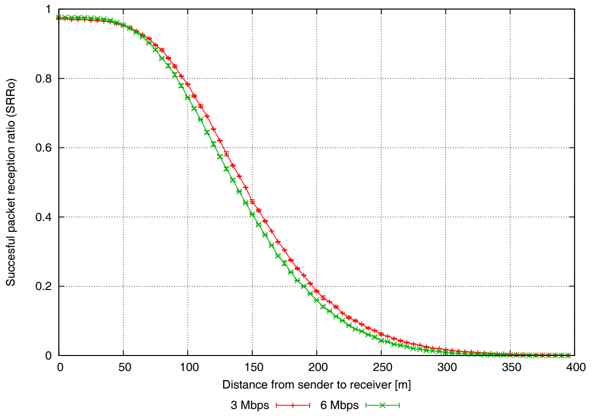
Metric	Unit	60 nodes/km		140 nodes/km	
		3 Mbps	6 Mbps	3 Mbps	6 Mbps
PGR	1/s	6.00	6.00	6.00	6.00
PTR	1/s	6.00	6.00	6.00	6.00
PTRo		1.00	1.00	1.00	1.00
CAT	ms	0.97	0.34	5.56	1.17
CBT		0.37	0.19	0.78	0.44

Table 6.8: Metrics of curves in Figure 6.3

We base our analysis on the comparison of both schemes in two scenarios with different node densities but identical other parameters. Figure 6.3 shows



(a) 60 vehicles/km

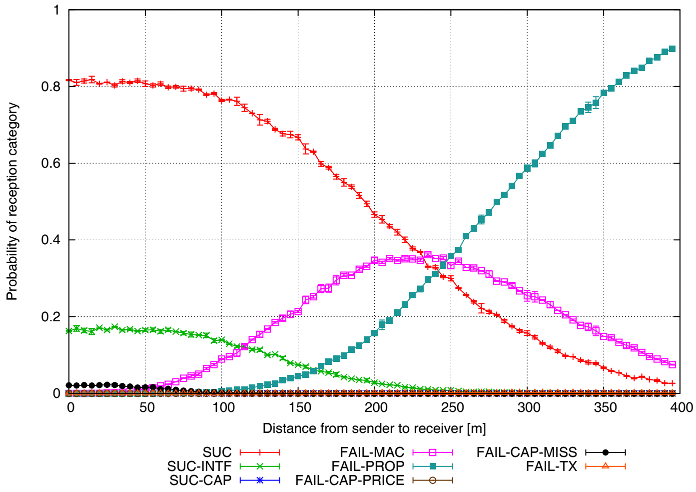


(b) 140 vehicles/km

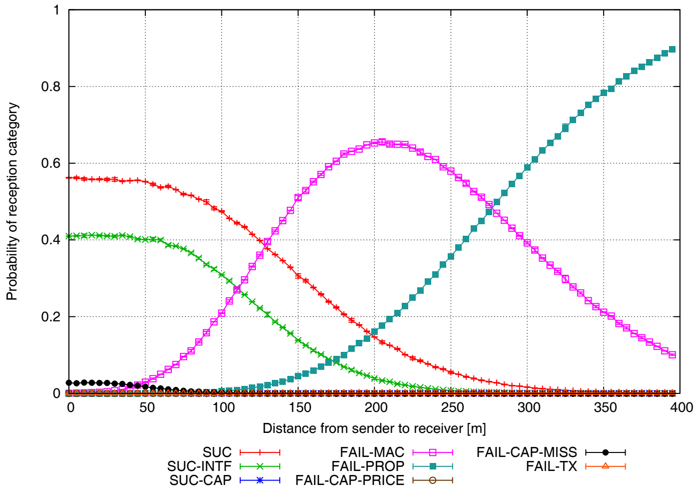
Figure 6.3: Successful packet reception ratio for different transmission rates / modulation schemes. Packets of size 500 bytes are transmitted with an intended range of 300 m, every node generates 6 packets per second, the contention window is set to 127. Nakagami m=3 is taken as propagation model, capture capabilities are disabled.

the SRRo for scenarios with 60 resp. 140 nodes per kilometer, a packet generation rate of 6 packets per second, contention window size of 127, 500 byte packets and a transmission power of 3.39 dBm while using the Nakagami-3 propagation scheme. In Figures 6.4 and 6.5 the corresponding reception category plots are provided for all four curves, and Table 6.8 provides the metric for all configurations. We make use of all available information in the following considerations.

First, we observe from Table 6.8 that all scenarios are chosen to be capable to transmit all generated packets, thus the load provided by each node is equal in all scenarios. First, when looking at Figure 6.3(a) we observe that the achieved SRRo over distance is either equal or lower at all distances for the 6 Mbps case due to the higher requirements necessary for a successful reception. By comparing the

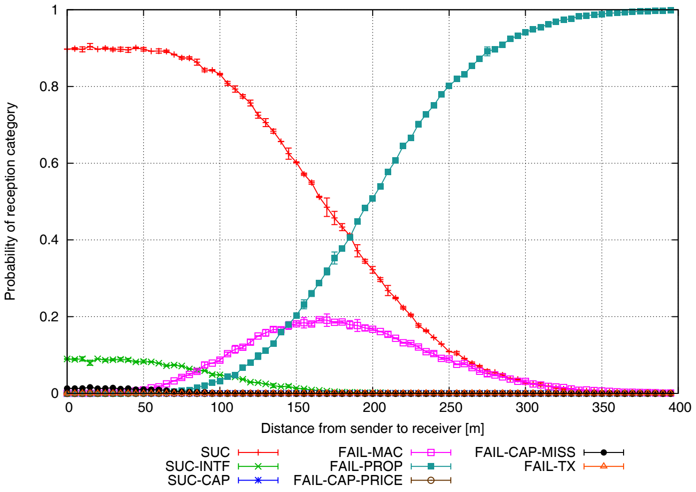


(a) 60 vehicles/km, 3 Mbps

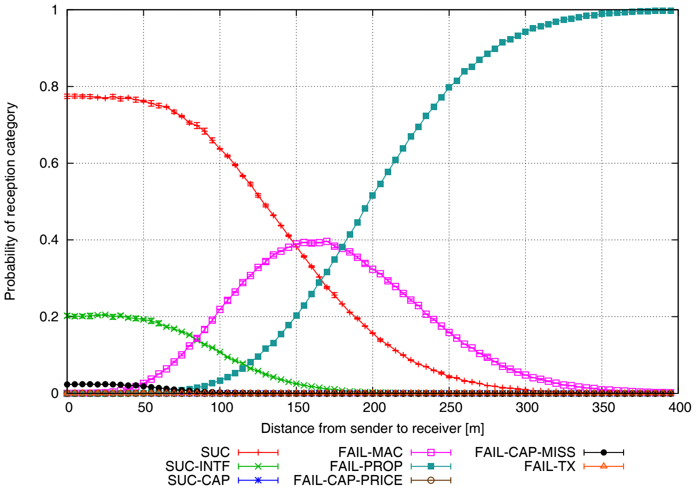


(b) 140 vehicles/km, 3 Mbps

Figure 6.4: Reception categories for different transmission rates / modulation schemes. Packets of size 500 bytes are transmitted with an intended range of 300 m, every node generates 6 packets per second, the contention window is set to 127. Nakagami m=3 is taken as propagation model, the capture capability is not activated.



(a) 60 vehicles/km, 6 Mbps



(b) 140 vehicles/km, 6 Mbps

Figure 6.5: Continuation: Reception categories for different transmission rates / modulation schemes. Packets of size 500 bytes are transmitted with an intended range of 300 m, every node generates 6 packets per second, the contention window is set to 127. Nakagami m=3 is taken as propagation model, the capture capability is not activated.

FAIL-PROP curves in Figures 6.4(a) and 6.5(a) we observe an increase of failed reception due to failing the reception requirements at closer distances for the scenario with higher density. Additionally, we observe the reduced probability of a collision (curve FAIL-MAC) in the distance from 100 to 300 m under 6 Mbps, but this effect cannot compensate the worse rates due to the radio (FAIL-PROP). When looking at Table 6.8 we see that a higher data rate leads to a lower CBT, it falls from 37 % to 19 % for the lower dense scenario. The reason is that packets need less time on the channel to be transmitted.

We now derive the effect of the modulation scheme when switching to a higher dense scenario. The comparison of each curve in Figure 6.3(a) and Figure 6.3(b) shows worse performance over distance for each individual curve under high density. In Table 6.8 we observe an increase of CAT and CBT. The analysis of reception categories shows for both modulation schemes a considerable increase of collisions (see the FAIL-MAC curves) and a tendency to more packets being received with interferences (SUC-INTF curves), thus we state that any scenario being more dense leads to an increase of collisions because the probability of hidden nodes is increased if there are more nodes positioned in the surrounding of each node, and the probability of transmitting in the same backoff slot is increased as well.

An interesting further observation is that the two curves in Figure 6.3(b) show similar behavior. The reception category analysis, however, shows that the similar slopes observed have quite different reasons, compare Figures 6.4(b) and 6.5(b). While, when going from BPSK to QPSK scheme, the FAIL-PROP curve always is higher at each individual distance, the FAIL-MAC curve always is lower. Thus, we again observe the trade-off of using a more advanced modulation scheme: from propagation phenomena together with reception requirements it always is contra productive with respect to distance, but the gain in less collisions by MAC due to the faster transmission dominates some of the losses.

Finally, it is interesting to observe that the scenario with low density and the 3 Mbps scheme and the scenario with high density and 6 Mbps scheme achieve comparable CAT and CBT. Looking at the ratios of categories of these two configurations, we see in Figure 6.4(a) and 6.5(b) that the slopes for the successful packets show similar slope and values, while the ones representing failed packets differ a lot.

Concluding, we can state that, after looking at all available data, it remains undecided currently what actually is the preferred scheme to be used. Yet, there is a broad simulation study that is built up on our simulation models and the simulator developed that exactly tackles the problem, see [Jiang et al. 2008]. As a result, the study observes that for most configurations it is advantageous to use QPSK modulation, thus, a data rate of 6 Mbps.

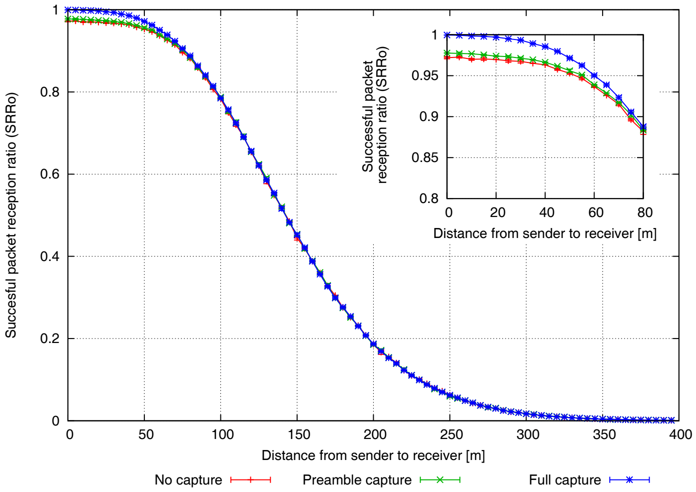
6.3.3 Receiver capture capabilities

We explore the potential of the capture capability of a chipset and identify under which system configurations the capability provides advantages. The capture capabilities are either switched off (capture disabled), activated during the preamble and header reception phase (preamble/header capture), or during complete packet reception phase (full capture). In Figures 6.6 and 6.7 the effect of capture for different packet generation rates and intended propagation distances is shown. The inset shown in the upper right corner enlarges the region of interest with respect to capture capability, high reception ratios in close distance to the transmitter. All plots show a scenario with a node density of 140 nodes/km for the Nakagami-3 propagation model and a contention window of 127. The transmission power as well as the packet size is varied in order to identify the consequences on performance with respect to capture.

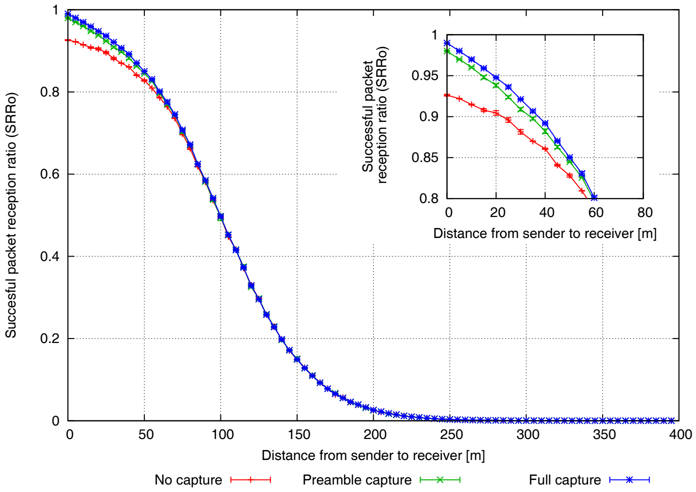
We observe that the capture capability becomes more relevant for scenarios where the medium is used more intensively. It particularly improves reception probability in near distances as packets from near distance have high probability to fulfill the capture requirements and are then capable to be received in spite of a reception of a weaker packet. As we can observe in all four plots, the capture capability during complete reception time is capable to increase SRRo up to 100 % in very close distances, where a reception without capture suffers from interferences. It should be emphasized that although the increase in SRRo is small in absolute terms (12 % for the most dense scenario) it is of major importance with respect to the expected applications from the safety domain where every additionally achievable information improves the application, or may even allow it at all.

We further observe that the capture capability leads to improved reception for short distance messages, up to a range of 50 m approximately. There is no improvement observable at further distances. Exemplary, and representative for the other plots, we now further analyze in detail Figure 6.7(a) by providing the metrics in Table 6.9 and the reception categories analysis for disabled capture and full capture in Figure 6.8. From the metrics we observe that the values do not vary a lot for the different variants of capture. As the presented metrics describe transmission behavior and channel utilization, capture will not change these metrics as it is an effect in the reception process at the receiver. Yet, if we relate reception behavior and the metrics, we see that we gain additional performance of the system when using capture capabilities: improved reception rate ratios in close distances are achieved without making more intensive use of the available resources.

From the reception category analysis we observe that a huge amount of packets (more than 55 % in distances up to 100 m) is only been received with interferences, see the SUC-INTF curve. In this scenario, the additional potential of capture is

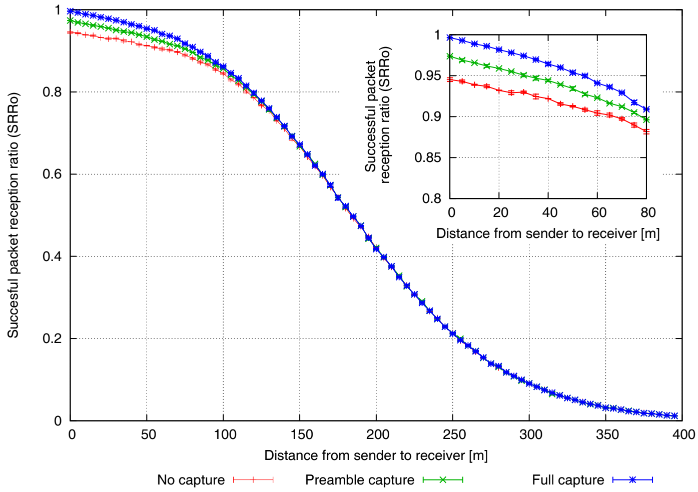


(a) 6 packets/s, 300 m intended distance

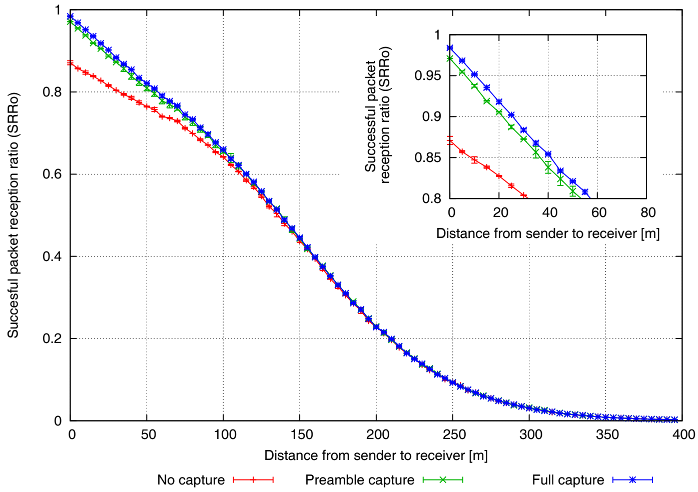


(b) 10 packets/s, 300 m intended distance

Figure 6.6: Successful packet reception ratio for different levels of capture support. Packets of size 500 bytes are transmitted with an intended range of 300 m, every node generates 6 / 10 packets per second, the contention window is set to 127. Nakagami m=3 is taken as propagation model and a data rate of 3 Mbps is used. The scenario has a density of 140 vehicles/km.



(a) 6 packets/s, 500 m intended distance



(b) 10 packets/s, 500 m intended distance

Figure 6.7: Continuation: Successful packet reception ratio for different levels of capture support. Packets of size 500 bytes are transmitted with an intended range of 500 m, every node generates 6 / 10 packets per second, the contention window is set to 127. Nakagami m=3 is taken as propagation model and a data rate of 3 Mbps is used. The scenario has a density of 140 vehicles/km.

Metric	Unit	Cap_Off	Cap_Pre	Cap_Full
PGR	1/s	6.00	6.00	6.00
PTR	1/s	6.00	6.00	6.00
PTRo		1.00	1.00	1.00
CAT	ms	33.67	34.43	33.93
CBT		0.95	0.95	0.95

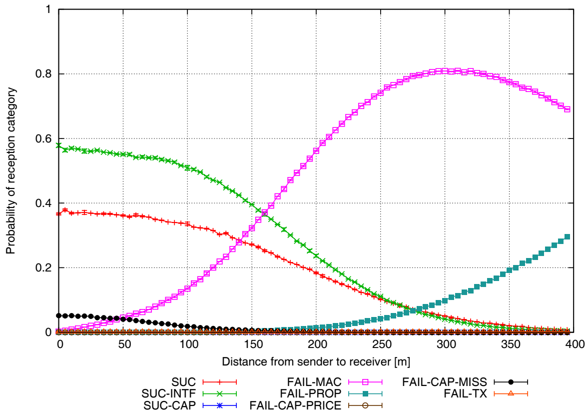
Table 6.9: Metrics of curves in Figure 6.7(a) (packet size 500 byte, generation rate 6 packets/s)

Metric	Unit	Cap_Off	Cap_Pre	Cap_Full
PGR	1/s	10.00	10.00	10.00
PTR	1/s	7.51	7.51	7.53
PTRo		0.75	0.75	0.75
CAT	ms	965.48	967.33	953.46
CBT		0.97	0.97	0.97

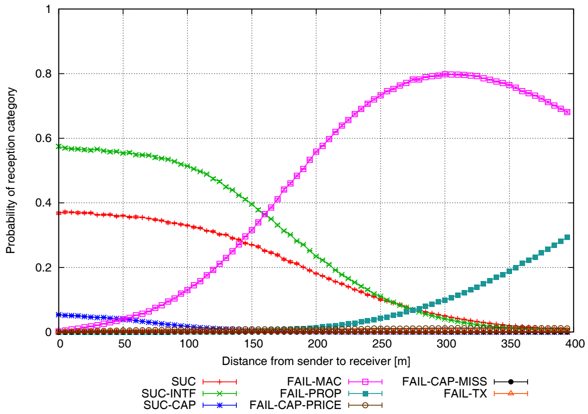
Table 6.10: Metrics of curves in Figure 6.7(b) (packet size 500 byte, generation rate 10 packets/s)

around 5 % in close distances up to 50 m. As mentioned, although the ratio is low, absolute reception performance can be increased closer to 100 % with the help of the additional reception possibility. In Figure 6.8(a), where capture capabilities are disabled, potential packets for capture are not received successfully, see the FAIL-CAP-MISS curve. In Figure 6.8(b) where we observe the same situation for the full capture being activated the curve FAIL-CAP-EXT represents the additional ratio of packets that can now be turned into packets being successfully received instead of being not received (note that the curve changed its color). We also observe that the cure FAIL-CAP-PRICE” remains very close to 0, thus, the “price” that has to be paid in terms of other packets not successfully received due to a successful capture is distributed over all distances.

Further we want to explore the strong and instant decrease of SRRo in Figure 6.7(b), we therefore provide the according metrics in Table 6.10. We observe that this scenario is highly saturated, see the CBT of 97 %, and only a fraction of the packets that are generated can actually be transmitted, see PTR and PTRo. The consequence are very long channel access times of nearly a second, yet note that these values exceed the time between packet generation, 100 ms, and thus mainly include waiting times in the queue that fills up in such a case. One can see that in consequence the reception rates directly fall, thus, such overload situations have to be avoided, as we will see later in the chapter. Yet, we can observe that the capture capability improves the reception in close distances considerably in such a satu-



(a) Capture disabled



(b) Full capture: capture during preamble, header and payload

Figure 6.8: Reception categories for different levels of capture support. The plots relate to Figure 6.7(a) (6 packets/s, 500 m intended distance)

rated scenario and leads to an advantage in case such situations should still occur.

We observe that the capture capability is a feature in the receiver setup that improves the probability in close distances, while not increasing channel usage. We see that the price that has to be paid is small. Under situations with high channel usage or even saturation, the capture capability still provides the improvement of reception in close distances and thus is an important counter measure to improve close-distance reception reliability under all configurations.

6.4 Sensitivity analysis: system parameters

In this section we provide phase 2 of the performance evaluation and consider the influence of different configuration parameters and their influence on the performance of the communication system. For each parameter considered we give a brief introduction and describe the major trends again with the help of representatively selected sample configurations.

6.4.1 Message size

We first consider the influence of the packet size. The packet size is a parameter that directly influences the load that the nodes contribute to the data traffic on the channel. We apply packet sizes from 100 byte up to 1,000 byte. The influence is shown in Figure 6.9 as well as in Tables 6.11 and 6.12. For two vehicle densities the influence is investigated under Nakagami-3 propagation, capture capabilities are fully activated, and the BPSK modulation scheme with 1/2 coding rate being chosen, leading to a data rate of 3 Mbps. The transmission power is set to 3.39 dBm (300 m intended distance), and a packet generation rate of 6 packets/s is configured, the contention window is set to 127.

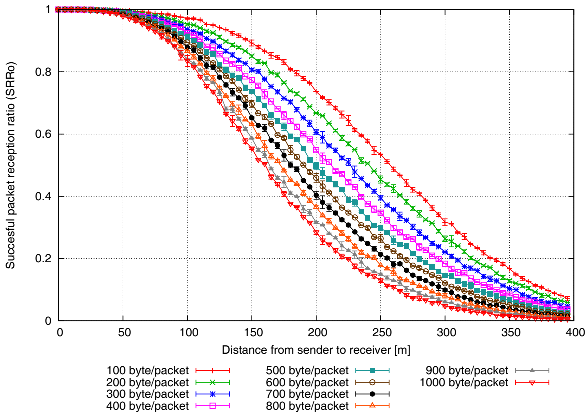
Metric	Unit	Packet size				
		100	300	500	700	900
PGR	1/s	6.00	6.00	6.00	6.00	6.00
PTR	1/s	6.00	6.00	6.00	6.00	6.00
PTRo		1.00	1.00	1.00	1.00	1.00
CAT	ms	0.17	0.47	1.01	1.80	3.14
CBT		0.10	0.24	0.37	0.50	0.62

Table 6.11: Metrics of the curves in Figure 6.9(a) (node density 60 vehicles/km)

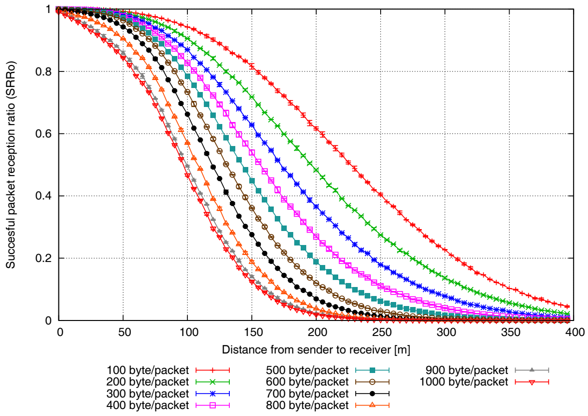
Metric	Unit	Packet size					
		100	300	500	700	900	1000
PGR	1/s	6.00	6.00	6.00	6.00	6.00	6.00
PTR	1/s	6.00	6.00	6.00	6.00	5.90	5.52
PTRo		1.00	1.00	1.00	1.00	0.98	0.92
CAT	ms	0.41	1.69	5.41	24.56	*199.01*	*503.36*
CBT		0.23	0.53	0.78	0.94	0.98	0.98

Table 6.12: Metrics of the curves in Figure 6.9(b) (node density 140 vehicles/km)

From the observation we see a clear and logic principal trend with respect to packet sizes: the larger the packets transmitted are the more intense the communication channel is used (see CBT) and the earlier the SRRo over distance plotted in the two figures begins to drop. For the node density of 60 vehicles/km the distance between the distinct curves appears highly regular, as does the increase in



(a) 60 vehicles/km



(b) 140 vehicles/km

Figure 6.9: Successful packet reception ratio for different packet sizes. Configuration: Nakagami-3 propagation, capture fully activated, 3 Mbps data rate, transmission power 3.39 dBm (300 m intended distance), packet generation frequency 6 packets/s, contention windows 127.

CBT. The widest spread can be observed at a distance of 200 m where the SRRo varies between 74 % for a packet size of 100 byte and 28 % for a packet size of 1,000 byte. It is notable again that CATs remain low for all packet sizes under low node density and that all generated packets can be transmitted.

If we consider the scenario with a node density of 140 vehicles/km we achieve further insights. Compared to the lower density, each curve behaves worse than its corresponding cure under low density. We also visually see that when increasing the packet size the decrease is much more intense than under low density and that curves spread much more. For large packet sizes we observe that the curves become similar in their shape and follow the same SRRo values over distance. Form Table 6.12 we see that for these large packet sizes the observed CBT is near 100 % and not all generated packets can actually be transmitted anymore. Thus, the curves for high packet sizes show the system performance under full medium saturation and provide a maximum possible load; we will discuss this phenomenon again in Section 6.5. We also observe that for high densities the reception probability starts to drop at small distances already, where we still achieve near-to-optimal performance under low vehicle density.

6.4.2 Message generation rate

We now review the influence of packet generation rate, the second parameter that directly influences the load contributed to the communication channel. For details on the configuration we refer to the last Section 6.4, with the difference that the packet size is fixed to 500 byte, and the packet generation rate is varied instead.

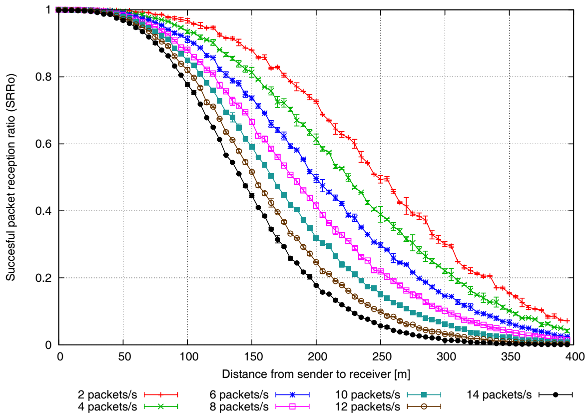
Metric	Unit	Message generation rate			
		2	6	10	14
PGR	1/s	2.00	6.00	10.00	14.00
PTR	1/s	2.00	6.00	10.00	14.00
PTRo		1.00	1.00	1.00	1.00
CAT	ms	0.25	1.01	2.32	5.57
CBT		0.13	0.37	0.60	0.79

Table 6.13: Metrics of curves in Figure 6.10(a) (node density 60 vehicles/km)

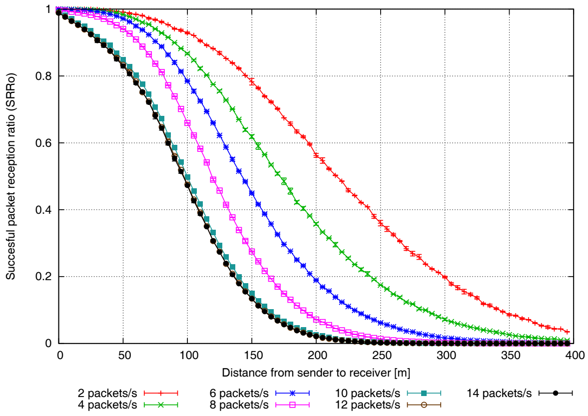
Metric	Unit	Message generation rate			
		2	6	10	14
PGR	1/s	2.00	6.00	10.00	14.00
PTR	1/s	2.00	6.00	9.86	9.91
PTRo		1.00	1.00	0.99	0.71
CAT	ms	0.67	5.41	*137.79*	*816.42*
CBT		0.28	0.78	0.97	0.97

Table 6.14: Metrics of curves in Figure 6.10(b) (node density 140 vehicles/km)

The result observed in Figure 6.10 and in the Tables 6.13 and 6.14 has strong similarities to the ones observed by varying packet sizes: a higher packet generation rate, and thus a more intensive request for channel resources leads to a decrease of reception probability, and in case that the wireless channel is saturated, to a convergence towards a minimum performance and a packet transmission rate that will not be exceeded. The similarities have the obvious reason that the influence on the system is the strongly similar when either increasing packet



(a) 60 vehicles/km



(b) 140 vehicles/km

Figure 6.10: Successful packet reception ratio for different packet generation rates. Configuration: Nakagami-3 propagation, capture fully activated, 3 Mbps data rate, transmission power 3.39 dBm (300 m intended distance), packet size 500 byte, contention windows 127.

sizes or increasing packet generation rate: a total higher load of data is generated. From an applications point of view, yet, the two parameters differ with respect to the achievable update rate.

For the lower dense scenario we see that the packets generated under all simulated rates can be transmitted to the channel. For the high density scenario, instead, we again observe that there is a limit that cannot be overcome; for the given configuration it is not possible to transmit more than 10 packets per seconds, what leads to a CBT of approximately 97 %. We again observe that CATs achieve very high values in the case of a saturated channel.

6.4.3 Message transmission power

Finally, we consider the important factor of influence of transmission power. The parameter differs from the other configuration parameters that were considered in its basic characteristic. While packet size and packet generation rate have an obvious way of influencing the system by defining the amount of data that each node requests to transmit the transmission power does not influence the system that directly. Instead, varying transmission power leads to a different large region being influenced either positively or negatively by the packet transmission. “Positive influence” includes the capability to successfully receive the transmitted message by another node, and “negative influence” includes the contribution to interference power on the transmission medium, thus causing noise that may hinder the reception of other packets. Thus, the adaptation of transmission power allows to adjust the spatial reuse on the medium. There is no simple way to precisely predict these positive and negative influences what makes transmission power control a challenging topic on its own.

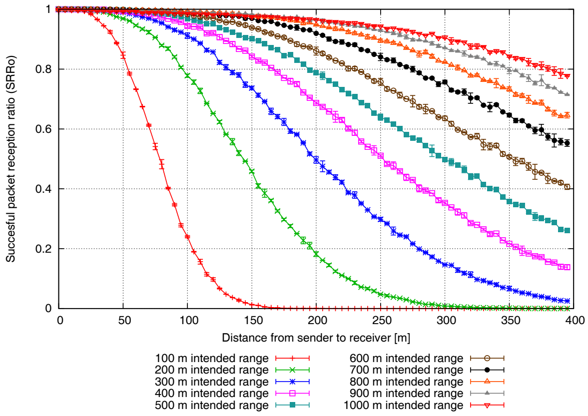
Metric	Unit	Transmission power				
		-0.14 dBm (200 m)	5.89 dBm (400 m)	10.08 dBm (600 m)	15.08 dBm (800 m)	18.96 dBm (1000 m)
PGR	1/s	10.00	10.00	10.00	10.00	10.00
PTR	1/s	10.00	10.00	10.00	9.98	8.71
PTRo		1.00	1.00	1.00	1.00	0.87
CAT	ms	1.17	4.04	11.81	70.74	*618.83*
CBT		0.42	0.73	0.89	0.96	0.97

Table 6.15: Metrics of curves in Figure 6.11(a) (node density 60 vehicles/km)

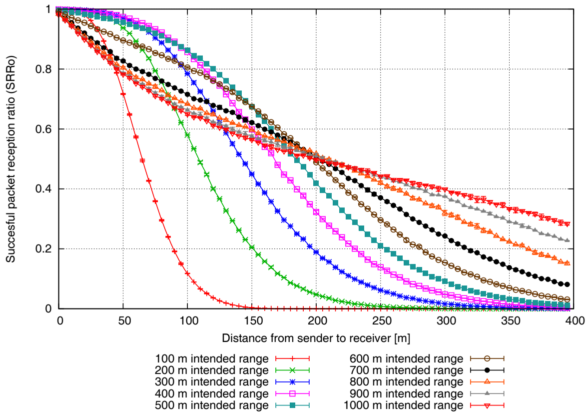
Metric	Unit	Transmission power				
		-0.14 dBm (200 m)	5.89 dBm (400 m)	10.08 dBm (600 m)	15.08 dBm (800 m)	18.96 dBm (1000 m)
PGR	1/s	10.00	10.00	10.00	10.00	10.00
PTR	1/s	10.00	8.52	6.68	5.35	4.49
PTRo		1.00	0.85	0.67	0.54	0.45
CAT	ms	11.02	*676.43*	*1,165.40*	*1,514.06*	*1,788.46*
CBT		0.87	0.97	0.97	0.97	0.97

Table 6.16: Metrics of curves in Figure 6.11(b) (node density 140 vehicles/km)

We again concentrate the discussion on the parameter analysis and consider two traffic densities of 60 and 140 vehicles per kilometer and show reception characteristics and metrics for the following configuration: Nakagami-3 propagation,



(a) 60 vehicles/km

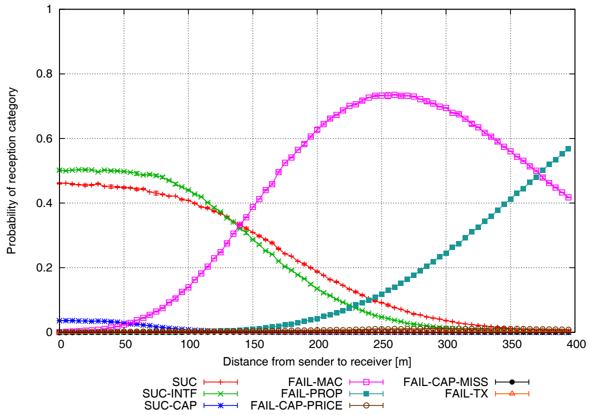


(b) 140 vehicles/km

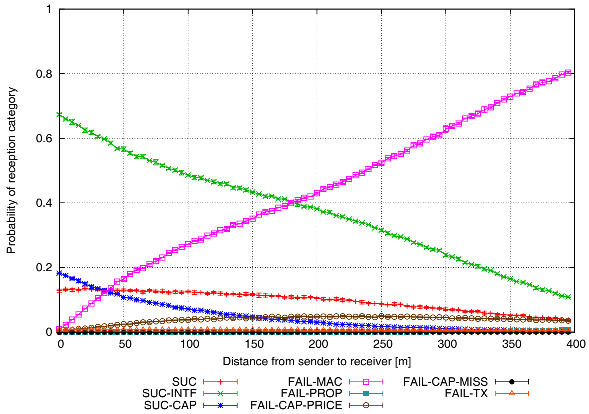
Figure 6.11: Successful packet reception ratio for different transmission powers. Configuration: Nakagami-3 propagation, capture fully activated, 3 Mbps data rate, packet size 500 byte, packet generation frequency 6 packets/s, contention windows 127.

capture fully activated, 3 Mbps data rate, packet size 500 byte, packet generation frequency 6 packets/s and contention window set to 127. The SRRo is shown in Figure 6.11, an the metrics are provided for a subset of the transmission powers in the Tables 6.15 and 6.16.

In Figure 6.11(a) we observe that, in principal, a higher transmission power also leads to improved reception probabilities in further distances. For the density shown highest reception rates at each distance are achieved with the highest power, while the worse performance is achieved with lowest power, and all transmission powers in between are well ordered between maximum and minimum power investigated. As such, a simple derived rule would result in always transmitting messages with highest possible transmission power. However, as shown



(a) 5.89 dBm transmission power (400 m intended distance)



(b) 15.08 dBm transmission power (800 m intended distance)

Figure 6.12: Reception and failure categories for different transmission powers and a node density of 140 vehicles/km.

in Figure 6.11(b), the situation changes if the density of vehicles is increased.

We observe that the selection of a higher power does *not* inherently lead to higher reception rates. First, we can derive from the Figure 6.11(b) that, apart from the considerably worse reception characteristics under all transmission powers when compared to lower density, there is a transmission power above which the reception behavior particularly in close distances becomes worse than the one when a lower power is used. The best performance with respect to SRRo up to a distance of 100 m is achieved when using a transmission of 5.98 dBm, what relates to an intended distance of 400 m. While the next higher transmission power tested still provides adequately good ratios, all higher transmission powers strongly suffer in close distances. The metrics in Table 6.16 show an additional consequence of using high transmission powers: the communication channel becomes that saturated that the achievable transmission rates (PTR) reduce with every further increase of transmission power.

The transmission power adjustment prominently shows the effect that interferences have on the performance of a communication system. High transmission powers in principle allow the reception in further distances, but in case that too many nodes make use of such possibility, the power sums up even in far distances and leads to immense problems to successfully receive packets. The reception and failure category analysis shown in Figure 6.12 provide further insights. Figure 6.12(a) shows the category ratios for an intended distance of 400 m (5.89 dBm transmission power) while Figure 6.12(b) shows the according curves for an intended distance of 800 m (15.08 dBm transmission power). Exemplary, we discuss the situation at 50 m distance from a transmitter. While in the first case 45 % of the packet can be received without any interferences (SUC curve) this amount is strongly reduced to 13 % in case of high transmission power due to the huge range that is covered by a transmission with high power. Further, we observe that the possibility to receive packets with ongoing interferences (SUC-INTF curve) increases from 49 % to 57 % but the loss in interference-free reception cannot be compensated. It has to be noticed that the capture capability involves an important role in scenarios with high transmission power and contributes 10 % to the successful reception ratio in 50 m, see curve SUC-CAP. Finally, it is obvious that packet losses due to packet collisions (FAIL-MAC curve) have increasing importance from closet distances onwards in case of high transmission powers, while for lower transmission power collisions mainly occur in medium ranges from the transmitter, but do not cause reception failures in close distance.

We observe that an adequate choice of transmission power is fundamental in order to optimize system performance. While low transmission powers only cover a small range of nodes, high powers induce a lot of energy on the wireless channel, leading to interferences and failed receptions even in far distances. We observe that the transmission power parameter becomes very sensitive in scenarios with high node density.

Several studies considered the adaption of transmission power under varying conditions and for different goals. In [Torrent-Moreno 2007] transmit power control was studied in order to not saturate the channel, enable the fair distribution of periodic status messages, and leave the possibility to transmit event-based emergency messages if needed. The algorithm used, Distributed Fair Power Adjustment for Vehicular environments (D-FPAV), was further optimized and presented in [Mittag et al. 2008]. In [Sepulcre & Gozalvez 2009] transmit power control is used by the OPortunistic-driven adaptive RAdio resource Management (OPRAM) algorithm such that nodes that should reliably be informed of an imminent danger have best possible reception reliability, while the channel is not used more intensive than necessary.

6.5 Overall systems analysis by local broadcasts capacity

In the last two sections we have analyzed the performance of the communication system under local broadcast transmissions and observed the behavior of the system performance for variations of the fundamental factors and configuration parameters. In this section we go one step further. Instead of observing behavior independently for each factor or parameter, we now take a systems view and want to analyze what is the best performance out of all possible configurations that a system can achieve. Therefore, we defined *local broadcasts capacity* in Chapter 4 that provides a metric to obtain how many bits per second each node may contribute to the medium such that it is still capable to provide the performance required by the applications. In Chapter 4.4 we derived theoretical limits: the maximum local broadcasts capacity $C_{\mathrm{LB,max}}$, and a worst case analysis for a setup that considers challenging system behavior and according models, $C_{\mathrm{LB,wc}}$. In difference to the theoretic considerations, we will now apply local broadcasts capacity for the simulations performed and can thus achieve a more realistic exploration of the capacity that can be achieved.

6.5.1 Simulation approach

The derivation of local broadcasts capacity by simulations is achieved by the procedure described in the following. First, the global input parameters channel data rate b, node density d, expected awareness range r and the required probability of reception within the awareness range p have to be given, thus, the simulative local broadcasts capacity $C_{\mathrm{LB,sim}}(b, d, r, p)$ is explored.

The data rate b is given by the modulation scheme and coding rate chosen for the simulation study. Simulations are run for all node densities d that should be considered. Also, several awareness ranges r and required probabilities p can be covered by one simulation study, as the influence of r and p is considered during the evaluation, and not in the simulation phase itself. The derivation of values for r and p depends on the application, e.g. for the EEBL application from Section 2.3.1 r=100 m and p considerably high, e.g. 95 %, are appropriate values[2].

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[2] Ideally, p=100 % could be the "real" requirement of a safety application. Yet, a communication system cannot achieve such a guarantee. Instead, we set the requirement to an achievable value per transmission, here p=95 %. Note that by considering multiple transmissions in common, higher

After having defined these conditions, simulations are run for the complete set of parameters presented in Section 6.1 and all simulations are evaluated with respect to the metrics defined in Section 6.2. In particular the Successful packet reception ratio (SRRo) is determined individually for all distances that are possible between two randomly selected nodes in the scenarios, the results are aggregated in bins of 5 m width.

The resulting statistics files are then evaluated. For each tuple of interest, consisting of awareness range and its related required reception probability, each simulation configuration is evaluated and it is checked whether the achieved SRRo at all distances smaller or equal to r exceeds the required reception probability p. If the condition is fulfilled, the average load that is contributed to the medium by nodes within the particular parameter configuration is determined. It is calculated as the configured packet size in byte multiplied by the packet transmission rate (PTR) that is achieved in the scenario. The parameter configuration and the load value are added to list of candidates for $C_{\text{LB,sim}}(b, d, r, p)$. Thus, among the configuration parameter space provided in Table 6.4, we select a set of possible scenarios out of the 2,100 configuration possibilities that are evaluated for every fundamental factor combination and every node density.

After the evaluation of all simulated configurations the one providing the highest load value (in bits per node and second) from the list of candidates is selected and $C_{\text{LB,sim}}(b, d, r, p)$ is assigned the according load. If several configurations achieve the same load the configuration that achieves the highest SRRo in distance r is selected as the representative configuration that is capable to provide $C_{\text{LB,sim}}$. If the list of candidates is empty, $C_{\text{LB,sim}}(b, d, r, p)$ is set to 0 as there is no configuration that is capable to fulfill the requirements. The procedure guarantees that the highest load under which the requirements are still fulfilled is selected. Obviously, the capacity derived by simulations can only take into account values from simulation configurations that have actually been run, thus, there remains the possibility that for other configurations a higher $C_{\text{LB,sim}}$ can be achieved. Yet, we perform the analysis for a broad variety of configuration parameters as listed in Table 6.4, in order to best possible cover the whole spectrum of configurations and consequently provide a good estimate for $C_{\text{LB,sim}}$.

6.5.2 Unconstrained capacity

First, unconstrained local broadcasts capacity is considered. As described in Section 4.5, the unconstrained capacity is the maximum load that a node is capable to provide to the medium and no other than the fundamental condition of local

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rates can be achieved, though with a possible longer delay until a successful reception occurs.

broadcasts capacity has to be fulfilled. In other words, the selection process considers all possible configuration parameters and does not take into consideration any other metric than SRRo.

In Figure 6.13 the local broadcasts capacity as it is derived from simulations and by the theoretical models presented in Section 4.4 is shown. The data used for the figure is taken from simulations that are run with a data rate of 3 Mbps, capture capabilities are fully activated, and the Nakagami-3 model is assumed as radio propagation model. In Figure 6.13(a) the local broadcasts capacities under theoretical maximum ($C_{\text{LB,max}}$), under theoretical worst case assumptions ($C_{\text{LB,wc}}$) and under the results obtained by the simulation approach ($C_{\text{LB,sim}}$) are shown over different awareness ranges r on the x axis and for different node densities d on the y axis. The required reception probability p is set to 0.95. On the z axis the maximum load that may be provided to the medium by each node is shown. The z axis is skipped at 50,000 byte/s such that higher achieved values of $C_{\text{LB,max}}$ are skipped and not shown. Further, the curves cover each other and not all data points can be seen in the figure.

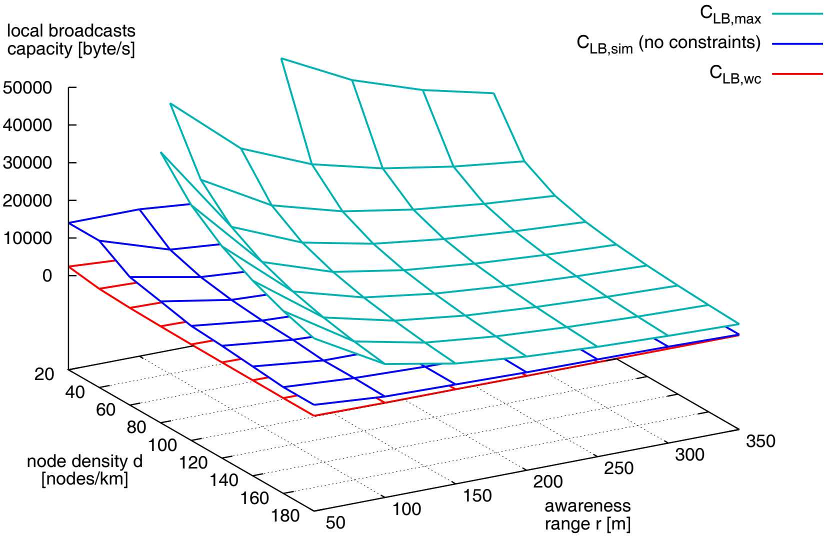
We can derive the following observations. First, we observe that

$$C_{\text{LB,max}}(b, d, r, p = 1) > C_{\text{LB,sim}}(b, d, r, p) > C_{\text{LB,wc}}(b, d, r, p) \tag{6.1}$$

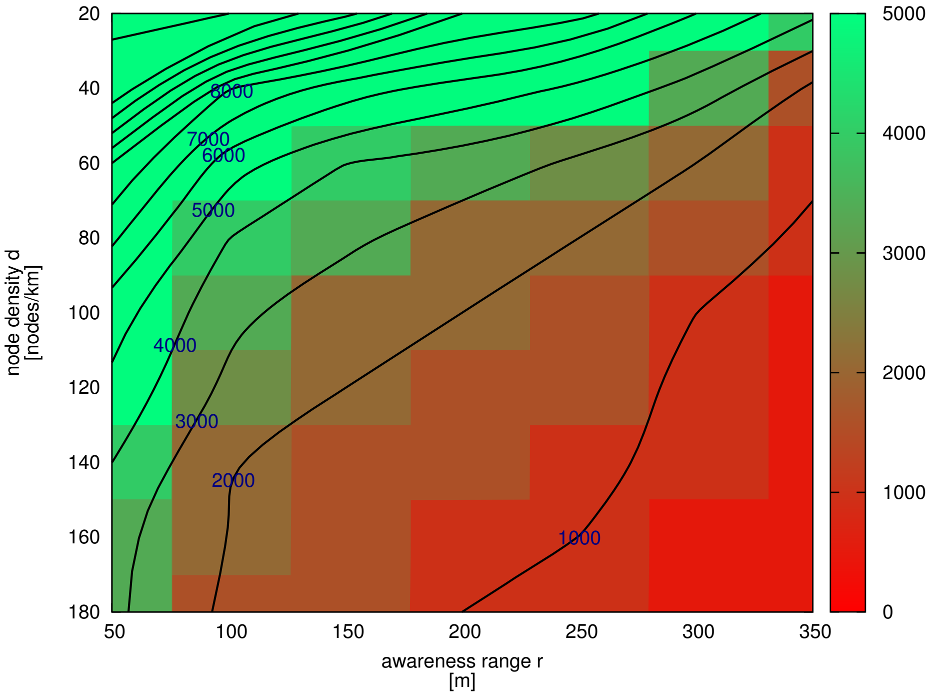
for b=3 Mbps, for all $d \in \{20, 40, 60, , 80, 100, 120, 140, 160, 180\,vehicles/km\}$, for all $r \in \{50, 100, 150, 200, 250, 300, 350\,m\}$ and for $p = 0.95$. Thus, we show that results by simulations fit in the range between the theoretically derived maximum and worst case capacity. The result confirms that the results observed by simulations that take into account the real mechanism and making more realistic assumptions with respect to the whole communication system and its components match neither of the theoretically derived extreme cases, but actually behaves between these two extremes as expected.

Second, we see that a principal trend is common to all local broadcast capacities: values achieved become lower when increasing the awareness range as well as when increasing the node density, leading to the arched shape of the plots. We also observe significantly higher absolute values under $C_{\text{LB,max}}$ than under $C_{\text{LB,sim}}$. In consequence, we derive that the interferences of realistic propagation behavior and the decentralized coordination of medium access does not allow to make use of all available capacity in real applied systems.

In Figure 6.13(b) the values obtained for $C_{\text{LB,sim}}$ are visualized as a colored contour map. The x and y axes are identical to Figure 6.13(a) shown above, but the values of the z axis are shown as colors where red represents 0 byte/s, green 5,000 byte/s and interpolated colors the different data rates in between. Values higher than 5,000 byte/s are also shown in green color. The values shown are dis-



(a) Three dimensional view on $C_{LB,max}$, $C_{LB,sim}$ and $C_{LB,wc}$



(b) Contour lines plot of $C_{LB,sim}$. The underlying color identifies $C_{LB,sim}$ in the range from 0 byte/s colored red to 5,000 byte/s colored green. Higher values are colored with light-green color as well.

Figure 6.13: Comparison of maximum, simulated and worst case C_{LB} for b=3 Mbps and p=0.95.

cretely derived by simulation for the values of d and r listed before. In order to improve the readability of the plot contour lines are shown as well in equal distances of 1000 byte/s. Each line is an isoline connecting the points with same value. As values are only available for discrete points, values in between are interpolated. Additionally the contour lines are plotted as B-splines, the respective function of the *gnuplot* tool is used for the calculation.

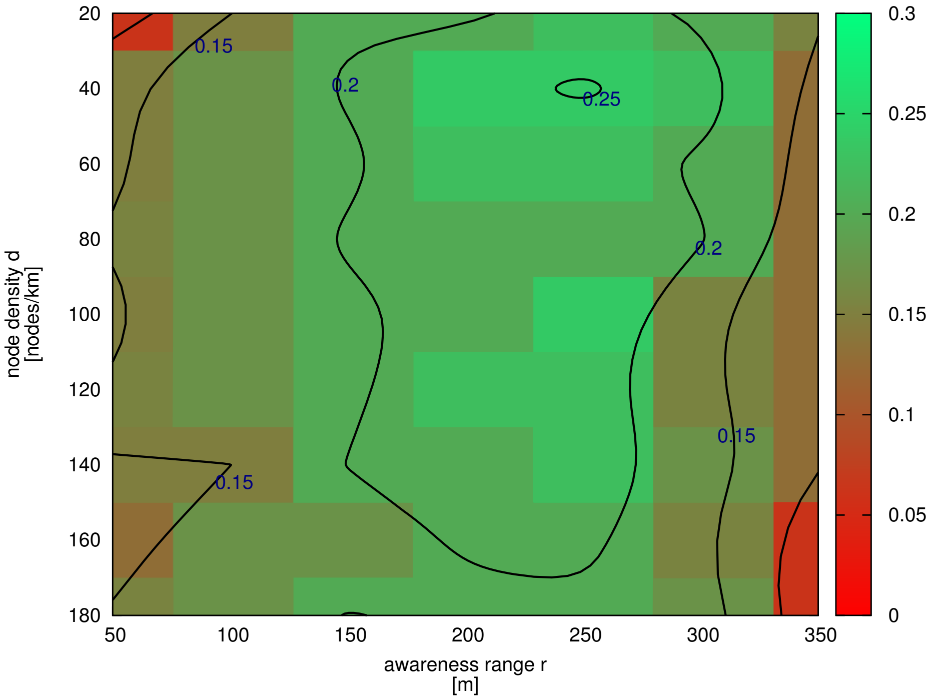
From the figure the local broadcasts capacity that is achievable for combinations of awareness range and node density can be easily derived and thus a better analysis is possible whether the achievable rate is still acceptable. For example, if each node provides a load of 5,000 byte/s to the system and want to cover an awareness range of 100 m, the system is capable to achieve that rate only up to a node density of approximately 70 nodes per kilometer. We further see that for a lot of combinations of r and d only very low capacities are achieved, what shows the limitations of the applicability of the system.

Next, the effectiveness of using the available capacity is explored. We therefore compare for each combination of r and d the capacity achieved in the simulations with the theoretically derived maximum value. For a fixed data rate b and a fixed required reception probability p the effectiveness ratio $e(d,r)$ at node density d and awareness range r is calculated as:

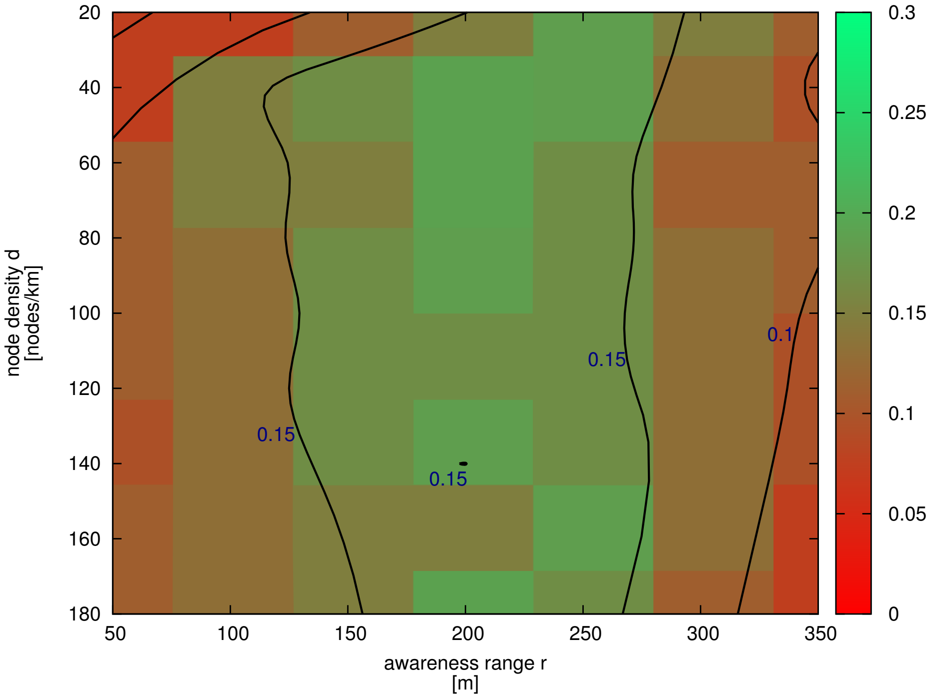
$$\begin{aligned} e(d,r) &= \frac{C_{\text{LB,sim}}(b,d,r,p)}{C_{\text{LB,max}}(b,d,r,p=1)} && (6.2)\\ &= \frac{C_{\text{LB,sim}}(b,d,r,p)}{\frac{b}{2dr}} && (6.3)\\ &= C_{\text{LB,sim}}(b,d,r,p)\frac{2dr}{b}. && (6.4) \end{aligned}$$

The achieved ratios are shown in Figure 6.14 as contour plots for simulations studies with 3 Mbps and 6 Mbps respectively. Again, the Nakagami-3 model is taken and capture capabilities are fully activated. The red-colored regions now represent configurations where 0 % of the maximum capacity is used, and green regions represent a usage of at least 30 %, the contour lines are drawn in equal distance of 5 %.

We achieve several observations. First, we see in both figures that large homogeneous regions arise. The areas particularly cover awareness ranges of medium size and spread over the complete set of node densities investigated. In consequence, the maximum available capacity can only be used up to a certain ratio and an approximate ratio of effective usage of theoretical maximum capacity can be derived for each combination of fundamental factors. For the 3 Mbps with capture fully activated and Nakagami-3 radio propagation an average effectiveness



(a) Data rate b = 3 Mbps (BPSK modulation, 1/2 coding rate)



(b) Data rate b = 6 Mbps (QPSK modulation, 1/2 coding rate)

Figure 6.14: Contour maps of effectiveness of capacity usage for p=0.95.

ratio of 17.5±4.22 % is achieved, averaged over all combinations of density and awareness ranges. As we see from the standard deviation there are derivations for some data points, yet, we have considerably low variations when respecting the broad range of variations that are covered by the average. If we only consider the “center” combinations, i.e. not taking into account the ratios of the highest two and the lowest two densities and awareness ranges, the average effectiveness ratio increases to 21.3±1.48 %. As we can also visually see in Figure 6.14 the effectiveness remains more homogeneous in this “center part”, what is confirmed by the lower standard deviation achieved.

Further, we observe that for both the lowest and the highest awareness ranges the ratio that is achieved decreases. Although the observation is the same the reason for the decrease differs for both extremes. For low awareness ranges the ratio decreases due to the reason that the communication system is not yet saturated and is capable to transport more data. Yet, in the simulations these high data rates were not requested by any of the configured scenarios. An extension of the simulation studies with configuration possibilities that provide a higher load is possible, but not done due the reason that for periodic broadcasts the spectrum covered with the used configuration parameters already is quite broad. For high awareness ranges, however, the opposite situation is the case. The wireless medium of the communication channel is strongly saturated and in order to provide the required reception probability at all nodes up the distance r the required performance is only achieved by the transmission of small packets with high transmission power. The resulting rate thus is considerably small and leads to a decrease of the effectiveness ratio.

We also observe that the ratio observed when evaluating the scenarios with a data rate of 6 Mbps is principally lower that the one observed with a data rate of 3 Mbps, thus, the effectiveness of using the medium is worse for the higher rate scenarios. As it was derived in Equation 6.4 the data rate b is considered in the calculation of the ratio, being in the denominator. In consequence, the absolute values achieved can still be higher for higher data rates, what actually is the case here. However, a higher data rate does not necessarily use the communication channel more effective in case of broadcast transmissions.

In Table 6.17 we provide for different combinations of scenario factors, the achieved average effectiveness ratios as well as the according ratios from the center combinations as described before. We first observe that under the deterministic Two Ray Ground model best effectiveness is achieved. We also see that the effectiveness is very low in case that the Nakagami-1 model is used as radio propagation model, an effectiveness of 4.5 % at maximum is achieved only. We also observe that the application of capture capabilities increases the effectiveness of

System factor selection			Average ratio	
Propagation	Capture	Data rate	total	center
Two Ray Ground	Disabled	3 Mbps	17.1	20.1
Two Ray Ground	Full	3 Mbps	22.8	24.1
Two Ray Ground	Disabled	6 Mbps	14.5	16.9
Two Ray Ground	Full	6 Mbps	36.6	39.2
Nakagami-3	Disabled	3 Mbps	9.7	10.2
Nakagami-3	Full	3 Mbps	17.5	21.3
Nakagami-3	Disabled	6 Mbps	7.6	9.2
Nakagami-3	Full	6 Mbps	13.5	16.9
Nakagami-1	Disabled	3 Mbps	1.9	1.8
Nakagami-1	Full	3 Mbps	4.5	5.2
Nakagami-1	Disabled	6 Mbps	1.2	1.4
Nakagami-1	Full	6 Mbps	2.9	2.7

Table 6.17: Effectiveness of capacity usage for different combinations of fundamental factors. The column “total" represents all combinations of densities and awareness ranges, while the column “center” does not not take into account the ratios of the highest two and the lowest two densities and awareness ranges.

the capacity usage, e.g. for Nakagami-3 and 3 Mbps the ratio increases from 9.7 % to 17.5 % when activating the capture capabilities. We see that the ratio from selected nodes is always higher than the one observed by all nodes. The trend that usage of maximum capacity is worse when using higher data rates, i.e. more advanced modulation schemes, is also present for all configurations. The availability of the presented numbers may provide the basis for an effective capacity control of the channel and lead to protocols and schemes to optimize the usage of the communication system.

Overall, we observe the following general trends with respect to the fundamental factors:

- Propagation model: Models that include stronger fading is directly related to a less effective use of the available channel capacity.
- Capture capability: Activated capture capabilities lead to a significant increase of effective channel usage.
- Data rate / modulation scheme: A data rate of 6 Mbps compared to 3 Mbps leads to less effective use in terms of relative ratio, but better usage with respect to absolute values[3].

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[3] Note that the result is currently limited to the two data rates presented. An evaluation of additional data rates and modulation schemes is left for future work.

Finally, we conclude that, for tested combinations of fundamental factors that take into account fading[4] and configuration parameters, the effectiveness of using the capacity of the wireless channel with communication techniques based on IEEE 802.11p never exceeds 22 % of the maximum achievable capacity. It is an open discussion now whether other techniques could make use of the channel more effectively or whether a technology improvement would provide better performance. It has to be kept in mind that techniques to optimize a single or a set of links do not help when considering communication with local broadcast characteristics.

6.5.3 Constrained capacity

In this section we discuss local broadcasts capacity from the point of view that, in order to provide the required communication quality to the applications, additional constraints have to be fulfilled. Thus, we extend the study of local broadcasts capacity by including additional requirements within the selection process described in Section 6.5.1. From a procedural point of view the selection process is refined and candidates that should be added to the list have to fulfill additional requirements. Such constraints reduce the list of possible candidates and in consequence, the local broadcasts capacity under constraints may be worse as some advantageous configurations cannot be considered for the constrained local broadcasts capacity. Thus, the constrained capacity always is at maximum equal to the unconstrained capacity, but often smaller as we will observe.

The following list contains examples of constraints that an application may require in addition. Note that the constraints may be subject to a restriction of the parameter range or may involve one of the general or distance dependent performance metrics presented.

- **Minimum acceptable packet size:** the content that has to be put into the packets may require a minimum size of the packets.
- **Minimum packet transmission rate:** the application requests that information updates are transmitted a minimum number of times per second.
- **Minimum successful packet reception rate:** the application requests that at all nodes within the awareness range at least a minimum number of packets per second is successfully received from each node within the receivers awareness range
- **Maximum average channel access time:** the average channel access time

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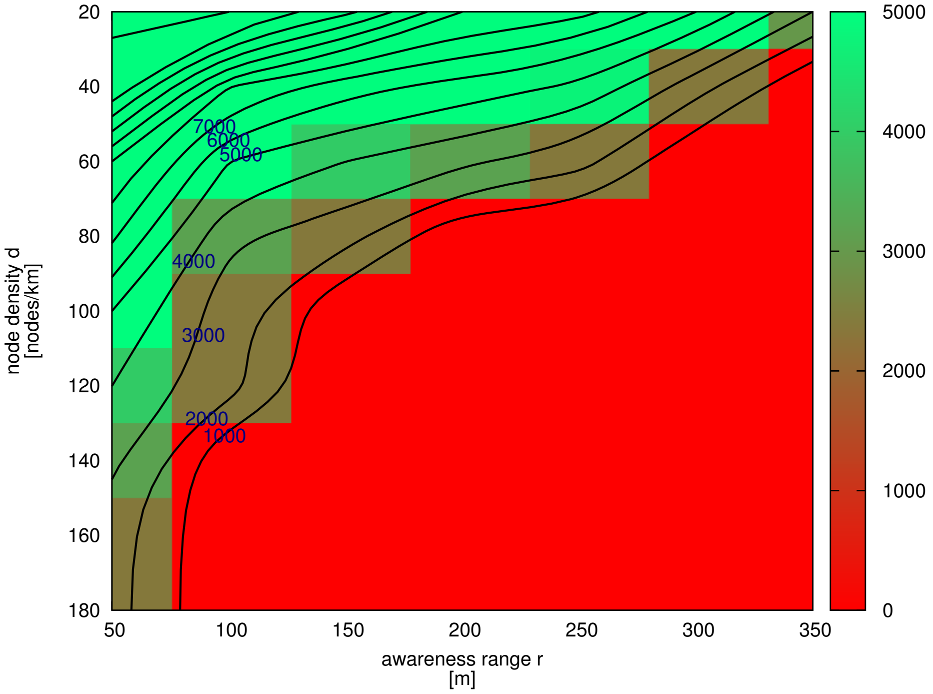
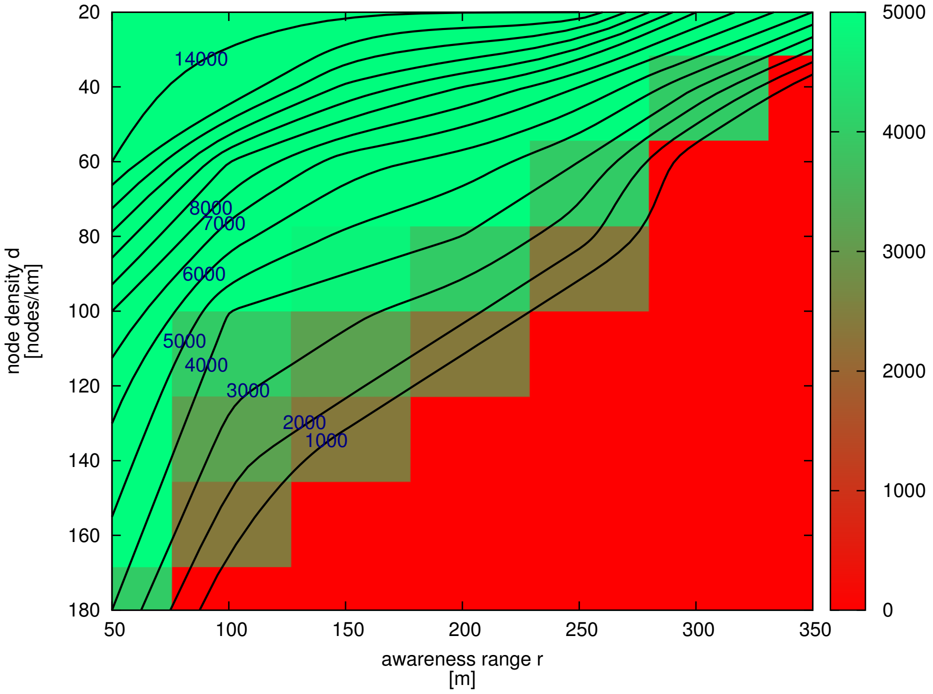
[4] We do not consider the results for Two Ray Ground now as it mainly serves as a setup to provide results for comparison that would only be achieved under unrealistic assumptions.



(a) Data rate b = 3 Mbps (BPSK modulation, 1/2 coding rate)



(b) Data rate b = 6 Mbps (QPSK modulation, 1/2 coding rate)

Figure 6.15: Contour maps of local broadcasts capacity with additional constraints for p=0.95 and under the additional constraints packet size $\geqslant$ 300 byte and successful packet reception rate $\geqslant$ 6 packets/s)

may not exceed a specific amount of time in order to guarantee that the message content contains up-to-date information

- **Maximum channel access time:** a maximum channel access time may never be exceeded in order to avoid outdated messages

We now exemplarily consider the case where two additional constraints have to be fulfilled. First, we assume that in order to put all information within the packets that are periodically transmitted, a minimum packet size of 300 byte is required, a reasonable assumption with respect to expected content and the necessary security overhead. Second, a successful packet reception rate of 6 packets per second from each individual node within the awareness range is expected by each receiver to receive up-to-date information regularly. The EEBL application in Section 2.3.1 might e.g. have requirements as considered here.

In Figure 6.15 we provide the constrained local broadcasts capacity as contour maps for data rates of 3 Mbps and 6 Mbps under the Nakagami-3 model, capture activated completely and p=0.95. Figure 6.15(a) can be directly compared to Figure 6.13(b) that shows the results for the unconstrained case. It is obvious that for many combinations of large awareness ranges and high node densities the local broadcasts capacity requirement and the requirements from the constraints in addition cannot be fulfilled, leading to a constrained local broadcasts capacity of 0 byte/s, see the large red colored area. Due to the higher amount of absolute data rate available, in case of additional constraints the data rate of 6 Mbps is capable to fulfill the constraints for more combinations of node density and awareness range.

6.6 Summary and impact

In the following, we first give a short overview where the detailed simulation studies have been used and applied as well. We then summarize the main observations that were achieved by the performance evaluation study. We first review work by our and other research groups that based on the improved and detailed simulation capabilities we developed.

- Simulation studies were intensively used to create a stochastical model of the reception characteristics of wireless channel. The stochastical model is applied in hybrid simulation approaches, in order to achieve scalability of simulations and being able to cover large scenarios and still provide accurate modeling of communication characteristics. We refer to our work [Killat et al. 2007], as well as to further achievements that are presented in [Killat & Hartenstein 2009] and [Killat 2009].

- In [Torrent-Moreno 2007] an earlier version of the simulator now publicly available was used to evaluate transmit power control techniques in V2V networks. The studies were further developed in our work [Mittag et al. 2008] and simulations were based on the provided code as well.
- In our work [Kuntz et al. 2008] the simulation code was the basis for the development of according models in the simulator OMNeT++. Cross validation to assure identical behavior was successfully applied in this study as well.
- Communication density, a metric to describe the channel load in V2V networks was introduced in [Jiang et al. 2007] and evaluated by intensive use of the simulation models presented here.
- In [Jiang et al. 2008], the precise simulation capabilities have been used to derive the optimal data rate that should be selected in V2V communication networks.

The performance evaluation study presented in this thesis provided the following major results.

- The intensity of small-scale fading has strong influence on local broadcast communication. Successful packet reception ratios decrease under simulations that make use of propagation models that consider severe fading. Fading further has strong influence on medium access mechanisms and thus causes even more severe situations. We observe that fading intensifies the impact of multi-user interference.
- Capture capabilities considerably improve reception rates in close distances to the transmitter, in particular under dense conditions, where the reception ratio can be increased being close to 100 %. Disadvantages are not observed. Capture capabilities improve the performance in communication distances of highest relevance for safety applications and thus are recommended to be implemented and applied.
- A modulation scheme that provides a higher data rate comes with the tradeoff between reduced time a single packet occupies the medium and the increased reception requirements to be fulfilled for successful reception. A definite answer was not observed in this study, but is given in the study [Jiang et al. 2008] that builds upon the simulation model that we developed and presented in this thesis. The rate of 6 Mbps was identified being the best one in most situations.
- Scenarios with low packet sizes and low message generation rates generally provide better reception performance. In consequence, unnecessarily

high packet sizes and generation rates should be avoided to keep load on the medium low. Under saturated conditions transmission rates as well as reception performance decrease and channel access times become unacceptably high.

- The selection of transmission power has strong influence on reception performance and on medium access control. Too high transmission power can cause a severe reduction of reception ratios due to strong interference even in far distance. In consequence, transmit power control is of fundamental relevance.
- Local broadcasts capacity enables overall system performance evaluation of local broadcast communication. Results derived by simulations fall into the range between theoretically derived maximum and worst case results. Local broadcasts capacity provides a feasibility analysis whether requirements of applications can be fulfilled, or not.
- The feasibility analysis is extended by respecting additional requirements from applications.
- For high node densities and high awareness ranges local broadcasts capacity decreases considerably.
- The effectiveness of using the capacity of the wireless channel is identified. In general, fading decreases effectiveness, capture capabilities increase effectiveness, and a higher data rate is less effective in relative terms, but more effective in absolute terms.
- Effectiveness remains close to an average value for a wide range of node densities and awareness ranges. An effectiveness factor can be derived for each combination of fundamental factors. When fading is considered the effectiveness ratio never exceeds 23 %.
- Local broadcasts capacity may provide an additional metric that can be used for distributed algorithms to improve communication with local broadcast characteristics.

7

Conclusions

The potential of direct wireless communication between vehicles on the road to improve traffic safety and traffic efficiency has been identified for a long time now and the development of communication solutions that are available for relatively low cost has attracted researchers and car manufacturers worldwide to develop, evaluate and establish suitable communication technologies. One technology that is currently under intensive discussion and standardization as a candidate to provide communication directly between vehicles as well as between vehicles and infrastructure devices is IEEE 802.11p, a derivate of the widely used IEEE 802.11 WLAN standard family.

In order to enable cooperative safety systems a key requirement for each application is the awareness that each vehicle has on its local surrounding. Apart from local technologies like radar systems, the periodic exchange of status messages of each node on a common shared wireless communication channel is a possibility to provide the necessary information to all vehicles in the surrounding. Practically, the status messages are transmitted as broadcast messages and all nodes in the geographic local surrounding are potential receivers of the messages.

Sharing one communication channel among all nodes leads to medium access problems and to the fact that the receivers may not be capable to successfully receive all messages. In particular, if the vehicle density is high and all vehicles request to transmit their periodic broadcast status messages on the shared communication channel it has been an open issue how the communication system actually behaves and how reliable the messages can be successfully received by nodes in the geographic surrounding of the transmitters. Specifically, the influence of interference at the receivers induced by wireless radio propagation characteristics (multi-path interferences) as well as the consequence of mutual interference of several status messages transmitted in parallel (multi-user interferences) is not clear when considering intensive local broadcast communication in dense vehicular networks.

In consequence, this work concentrated on the performance evaluation of periodic local broadcast communication, the identification of the influence of the different interference effects, and on the derivation of system performance limits. In order to do such an evaluation a concept and metric, local broadcasts capacity, was developed that expresses the capability of a system to provide the communication service requested by applications with the required reliability. A strategy and methodology was identified for its evaluation, consisting of analysis, modeling, simulation and assessment.

First, current research was reviewed, in particular a vehicular safety application and its requirements on communication was discussed. Further, current research projects and the standardization of wireless communication technology were reviewed, and particularly, the development of IEEE 802.11p and related activities were considered and described in detail. We then discussed fundamental and related work with respect to the identification of radio propagation effects and potential sources of interferences. These activities formed the underlying basis of the work of this thesis.

We then derived a specific measure that allows evaluating the communication pattern of periodically transmitted broadcast messages containing relevant status information for all nodes in the geographic surrounding of the transmitting node. *Local broadcasts capacity* C_{LB} was defined with respect to the data rate a communication system is capable to provide, the density of vehicles, an awareness range that has to be covered by the broadcast messages and a ratio that identifies the minimum required probability of successful packet reception at nodes within the awareness range. C_{LB} measures the data rate each node can provide to the system such that the required reception probability within the defined awareness range can still be guaranteed. We carried out a theoretical analysis of local broadcasts capacity and, on the one hand, derived an upper bound, the theoretical maximum data rate, while on the other hand, we did a worst case analysis. The contributions of this part of the thesis include the derivation and definition of local broadcasts capacity as well as its theoretical analysis.

Theoretical analysis becomes highly complex and has its limits when considering scenarios of large scale and when considering more realistic assumptions with respect to protocol behavior, physical effects and environmental influences. In consequence, in close collaboration with Mercedes-Benz Research & Development North America we applied and developed models that allow a more realistic description and representation of inter-vehicle communication systems. In particular, the communication channel, the physical and the medium access layer of IEEE 802.11p WLAN chipsets are modeled in much more detail than it was typically done in the field of simulations with respect to the performance evaluation of wireless networks in the vehicular domain. The proposed models have been integrated and implemented in the widely used network simulator NS-2 and provide a complete overhaul of the medium access and the physical layer of the network simulator. The modules have been intensively reviewed by and discussed with other researchers in the domain and have become an integral part of today's standard distribution of the NS-2 simulator. The result is a simulator that enables detailed simulation and accurate studies that cover the highly relevant effects with respect to interferences. A simulation toolset that allows the efficient use of the simulator as well as statistically sound evaluation of the results has been developed as well. The contributions of this part of work are the development of models to represent communication specific aspects in the simulations in detail as well as the application of the models to a freely available and widely used simulation tool.

The developed simulation toolset including the NS-2 simulator was then used as the basis for a broad assessment by an evaluation study in order to identify the performance of vehicular communication networks for local broadcast communication. Particular focus was put on identifying the influence of interferences on the performance that is achieved. The simulation scenario considered that all nodes in the scenario periodically transmit status information messages with the intent that nodes in the geographic surrounding receive the messages and thus are aware of the status (e.g. position and speed) of the surrounding nodes. Simulations were performed for a wide range of vehicle densities and a combination of the fundamental system factors radio propagation, modulation scheme and coding rate and, the capture capabilities of receiver chipsets. A large set of configuration parameters was defined and simulations were run for each possible combination. The results were used to provide an analysis on the influence of the fundamental factors and on the influence of the configuration parameters, thus, the sensitivity of the system with respect to the parameters. We derived the major influence of the propagation models on the intensity of occurring interferences and consequently on the local broadcast performance of the system. We also observed that advanced receiver chipsets that support capture capabilities considerably improve the reception performance in close distances to the transmitter. We further identified multi-user interference to significantly influence the performance in particular in dense networks. The usage of high transmission powers strongly increases the impact of interferences and can suppress a better system performance. The contributions of this part of work are a detailed understanding of the sensitivity and influence of fundamental system factors and communication parameters on local broadcast performance. Such detailed understanding is an essential basis for the further development of applicable and adaptive communication protocols.

Finally, we analyzed local broadcast communication from a system-wide perspective and analyzed the local broadcasts capacity that derived from the simulation studies. We observed the achieved capacity for varying node densities and awareness ranges and identified several regularities. First, we observed that the results derived by simulation perfectly fit between the theoretically derived results on maximum and worst case capacity. We also identified, as one would expect, that the achievable capacity reduces when awareness ranges are increased and when the node density is higher. The ratio of the capacity achieved by simulations and the theoretical maximum capacity, thus, the effectiveness with which the available capacity of the medium is used, remains essentially constant over a wide range of awareness ranges and densities and only varies marginally. The maximum ratio achieved over all simulated configurations is 23 % for a required reception probability of 95 % within the awareness range. The availability of such fundamental and general dependencies provides the possibility to develop adaptive algorithms that, by extracting information from ongoing communication, may control communication in such a way that the data rates provided by each node do not saturate the communication system and by that allow providing performance assurances within the network. The achievable local broadcasts capacity was also derived under additional constraints that allowed identifying the principle limitations of local broadcasts communication. The contributions of this part of work are the assessment of overall system performance of local broadcast communication and the identification of fundamental dependencies that can be used for future system design and the development of adaptive protocols.

As a final conclusion, we state that this thesis delivered contributions with respect to different scientific aspects. First, the discussion of local broadcast communication identified the challenges of this type of communication and the derived local broadcasts capacity metric proposed a method to identify the performance analytically and by simulations. Second, the developed models and their implementation in a network simulator provided accurate tools to the research community to perform detailed network simulation studies that respect the particularities of the physical layer and the communication channel in vehicular networks. Third, the local broadcasts capacity concept and the developed simulation tools are applied in a comprehensive performance evaluation study that on the one hand provided fundamental insights into the influence of system factors and parameters, and on the other hand it enabled the evaluation of broadcasts communication from an overall system's perspective. The effectiveness with which the communication system makes use of the the theoretical maximum capacity of the communication channel was identified. The results achieved give fundamental insights of communication system performance under intensive broadcast traffic and for high and challenging vehicle densities. The work thus allows predicting the system performance to be expected when, in the future, most vehicles will be equipped with communication technology and it provides fundamental insights the have strong relevance and impact for the further development of vehicular communication systems and of algorithms that enable the efficient use of the communication channel.

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WWW C2C-CC
Website of the CAR 2 CAR Communication Consortium `http://www.car-to-car.org/`

WWW C2C-CC Manifesto
CAR 2 CAR Communication Consortium Manifesto - Overview of the C2C-CC System `http://www.car-to-car.org/fileadmin/downloads/C2C-CC_manifesto_v1.1.pdf`

WWW CALM
Website if the ISO TC204 WG16: CALM (Communication Architecture for Land Mobile) `http://www.isotc204wg16.org/`

WWW CICAS
Website of the California Cooperative Intersection Collision Avoidance System (CICAS) Project `http://www.viicalifornia.org/projects/intersection.html`

WWW COMeSafety
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Website of the Co-operative Systems for Intelligent Road Safety (COOPERS) Project `http://www.coopers-ip.eu/`

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WWW PRE-DRIVE C2X
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WWW PReVENT
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WWW Sevecom
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