Self-Organizing Communication in Vehicular Ad Hoc Networks

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Abstract

Digital communication plays a crucial role in the automotive domain: Within the vehicle, various communication busses are integrated, which connect controllers, sensors and actuators. Fixed base stations at the roadside allow a wireless communication of vehicle and passengers with the environment via public radio and cellular phone networks. A newer approach is to enable also a direct communication between vehicles. Vehicles equipped with a self-organizing wireless ad hoc communication system form a Vehicular Ad Hoc Network (VANET) for exchanging data on the locally seen road and traffic status. This information allows a driver assistance system to be aware of the local situation in a wide area (> 10 km). In this way, it can provide up-to-date travel and traffic information such as the traffic status or hazard and emergency warnings.

This thesis investigates techniques for comfort applications in VANETs that disseminate data in a large area. The focus is on two aspects: The first is VANET communication in case of a low number of vehicles equipped with the ad hoc communication system, the second is avoiding congestion on the wireless link in situations with a high density of vehicles using the system. Both issues are of fundamental importance for a large scale deployment of a VANET.

In particular during the phase of market introduction, conventional dissemination schemes known from other types of ad hoc networks are not suitable for VANETs. The main reason is that these schemes try to create a wireless multi-hop connection between source and sink of information. If a low number of all vehicles use the self-organizing wireless communication system, the network is merely connected in small parts and information can only be disseminated in a small area by multi-hop communication. Therefore, the thesis investigates an alternative approach which allows to disseminate information in a wide area even for a low penetration of 1-2 % of the ad hoc system. Gaps, where no wireless communication is feasible, are closed by transporting the data onboard vehicles of the opposite lane. An extension of the dissemination technique additionally provides a self-generated road map based on track information of other vehicles.

The second focus of the thesis is on efficiently using the available wireless bandwidth. A novel concept for utility-fair broadcast is presented in which the vehicles

adapt their data rate dynamically according to the local situation on a per-packet basis. It is shown that this leads to a very efficient data dissemination and a controlled load on the medium even in case of a high density of equipped vehicles. Manufacturer specific VANET applications are supported by a store-and-forward module onboard all vehicles. This controlled sharing of the wireless link improves the speed of data dissemination significantly for VANETs where 5% or more vehicles are equipped.

The advocated techniques are evaluated by a combination of network simulation and a microscopic vehicular traffic model. Additionally, an experimental implementation in form of a Self-Organizing Traffic Information System (SOTIS) is presented. It demonstrates that a realization on existing wireless communication hardware is feasible.

Zusammenfassung

Kommunikationstechnologien spielen eine zentrale Rolle im Automobil: Innerhalb des Fahrzeugs vernetzen verschiedenste Bussysteme Steuergeräte, Sensoren und Aktuatoren. Feste Basisstationen am Straßenrand ermöglichen über Rund- und Mobilfunksysteme eine drahtlose Kommunikation des Fahrzeugs und seiner Insassen mit der Umgebung. Ein neuerer Ansatz besteht nun darin, auch den direkten Datenaustausch zwischen Fahrzeugen zuzulassen. Ausgestattet mit einem selbstorganisierenden Funksystem bilden die Fahrzeuge in ihrer lokalen Umgebung spontan ein drahtloses Netzwerk (Vehicular Ad Hoc Network, VANET). Mit Hilfe der ausgetauschten Informationen kann ein Fahrerassistenzsystem die Situation in einem sehr weiten Umkreis (> 10 km) erfassen. Der Fahrer erhält so hochaktuelle Verkehrs- und Reiseinformationen sowie Gefahrenwarnungen für sein lokales Umfeld.

Die vorliegende Arbeit untersucht Techniken für Komfortapplikationen, die eine Datenverbreitung über große Entfernungen in einem VANET ermöglichen. Hierbei werden vor allem zwei Fragestellungen behandelt, die für den Einsatz eines solchen drahtlosen Netzes von zentraler Bedeutung sind: die Kommunikation bei geringen Ausstattungsgraden sowie die Vermeidung von Überlastsituationen bei stärkerer Verbreitung des Systems.

Insbesondere in der Einführungsphase sind konventionelle, von anderen Ad-hoc-Netzen bekannte Verfahren ungeeignet für die Datenverbreitung in einem VANET. Diese Verfahren beruhen darauf, eine Funkverbindung zwischen Informationsquelle und -ziel über weiterleitende Fahrzeuge herzustellen (Multi-Hop Ansatz). Da bei geringen Ausstattungsgraden nur in kleinen Abschnitten Funkkommunikation möglich ist, erfolgt auch die Datenverbreitung nur innerhalb eines kleinen Bereiches. Daher wird ein neuer Ansatz untersucht, der auch bei nur 1-2 % Ausstattung Daten über große Distanzen verbreiten kann. Lücken im VANET, in denen keine Funkkommunikation möglich ist, werden durch Transport der Daten an Bord von Fahrzeugen der Gegenfahrbahn geschlossen. Eine Erweiterung des Verfahrens generiert zudem Informationen zum Straßenverlauf selbstorganisierend aus den Fahrwegen anderer Fahrzeuge.

Der zweite Schwerpunkt der Arbeit behandelt die effiziente Nutzung der zur Ver-

fügung stehenden Bandbreite. Es wird ein neues, anwendungsunabhängiges Konzept vorgestellt, bei welchem die Fahrzeuge jedes auszusendende Datenpaket hinsichtlich des Nutzens für das Netzwerk bewerten und die in Anspruch genommene Datenrate dynamisch an die lokale Situation anpassen. Dies führt zu einer sehr effizienten Weiterleitung von Daten und Vermeidung von Überlast selbst bei einer hohen Dichte von ausgestatteten Fahrzeugen. Zur Unterstützung von herstellerspezifischen Anwendungen, die nur auf wenigen der mit dem Funksystem ausgestatteten Fahrzeuge aktiv sind, wird ein Weiterleitungsmodul eingesetzt. Dies erhöht die Geschwindigkeit der Datenverbreitung bereits bei Ausstattungsgraden ab 5 % erheblich.

Die vorgeschlagenen Techniken werden mit Hilfe einer Kombination von Netzwerk- und Verkehrssimulation bewertet. Die experimentelle Implementierung innerhalb eines selbstorganisierenden Verkehrsinformationssystems zeigt zudem, dass sich die Verfahren auf existierenden Systemen realisieren lassen.

Vorwort

Die vorliegende Arbeit entstand während meiner Zeit als wissenschaftlicher Mitarbeiter am Institut für Nachrichtentechnik der Technischen Universität Hamburg-Harburg. Zum Gelingen hat ganz wesentlich Herr Prof. Hermann Rohling beigetragen – sowohl durch seine engagierte Betreuung meines Dissertationsvorhabens als auch durch das motivierende Klima am Institut. Die Erfahrungen, die ich dort während der Mitarbeit in verschiedenen Forschungsvorhaben, Drittmittelprojekten, bei Fachkonferenzen und in der Lehre sammeln konnte, möchte ich nicht missen.

Für die Übernahme des Zweitgutachtens und interessante wissenschaftliche Diskussionen danke ich herzlich Herrn Prof. Hannes Hartenstein. Zudem gilt mein Dank Herrn Prof. Jan Luiken ter Haseborg, dem Vorsitzenden des Prüfungsausschusses.

Den ehemaligen Kolleginnen und Kollegen bin ich für die ausgesprochen gute und konstruktive Zusammenarbeit dankbar. Dr. André Ebner danke ich für die vielen fachlichen und persönlichen Gespräche, die von Anfang an maßgeblich die Richtung der Arbeit beeinflusst haben. Nico Tönder und Dr. James Groß haben mit einer Vielzahl an Anmerkungen wesentlich zu einer verbesserten Darstellung der Ergebnisse beigetragen. Allen Studenten, die mich innerhalb von Diplom- und Studienarbeiten oder als studentische Hilfskraft unterstützt haben, möchte ich ebenfalls danken.

Neben dem universitären Umfeld haben mir enge Freunde, meine Eltern und ganz besonders meine Frau Lena geholfen, die bei einem solchen Projekt auch immer vorhandenen schwierigen Momente zu bewältigen. Ohne diesen persönlichen Rückhalt wäre die Fertigstellung der Arbeit nicht möglich gewesen.

Ingolstadt, im Mai 2007 *Lars Wischhof*

Contents

1 Introduction

Electronics have become the main driver of innovation in the automotive industry. It is estimated that 80% of newly introduced features are enabled by novel electronic and software components. One major area for new comfort and safety applications is automotive telematics: the integration of computing and telecommunication technologies in vehicles. State-of-the-art vehicles apply telematic systems in dozens of different areas: Cellular phones, Digital Audio and Video Broadcast (DAB/DVB), receivers for the Global Positioning System (GPS), Bluetooth adapters to integrate personal digital assistants and phones, navigation systems with dynamic route calculation and automatic distress call/Enhanced 911 (E911) services are some typical examples.

An independent recent development in the wireless communications sector is the Mobile Ad Hoc Network (MANET): a dynamic network without any dedicated infrastructure. Mobile nodes communicate using a wireless network interface, either directly or using intermediate nodes to forward data packets to the destination. A typical scenario is a conference room where the notebooks and handhelds of the attendees form an ad hoc network during the meeting for collaborative work.

Given the important role of telematic services, the question arises if ad hoc communication can also be successfully applied in the automotive sector. An ad hoc network formed by the vehicles in a local area – a Vehicular Ad Hoc Network (VANET) – enables vehicles to directly communicate and inform each other of their local situation. For example, a vehicle recognizing a traffic jam or a hazard on the road can use the VANET to inform approaching vehicles. Based on the information received via the wireless link, driver assistance systems are able to warn the driver or adapt the route to the destination accordingly. By ad hoc communication, a driver is aware of the traffic conditions in an area significantly exceeding the range of human perception or automotive sensors installed in the vehicle. Furthermore, data received from access points at the roadside, e.g. at gas stations, can be exchanged via VANET and allow the driver to get up to date travel information such as gas prices or tourist news.

In contrast to existing cellular networks, no infrastructure is required and communication is provided free of charge. And due to the direct information exchange between vehicles, telematic services in the VANET can provide information with lower delay and a higher level of detail for the local area compared to existing solutions such as the public radio systems.

While the application of ad hoc communication between vehicles is therefore very attractive, several challenges remain. The mechanisms applied in conventional ad hoc networks are developed for low mobility of individual nodes and a relatively stable resulting network topology. In contrast, VANETs are characterized by a highly dynamic topology due to the high relative velocities of vehicles and specific movement patterns.

This thesis focuses on two key challenges for the application of VANET technologies: During the phase of market introduction which can last several years, VANET applications need to be able to cope with low connectivity due to a low penetration of vehicles equipped with the ad hoc communication system. Therefore, the first main aspect, which is evaluated, is data dissemination in VANETs where only a very low number of all vehicles are equipped with the ad hoc communication system.

The second focus of the thesis is a fair sharing of the available wireless bandwidth. With increasing number of VANET-equipped vehicles, it becomes mandatory to control the load on the wireless link. Otherwise, situations with a high density of vehicles result in a large number of packet collisions and a waste of bandwidth for redundant or less important transmissions. In contrast, a fair sharing of the wireless link leads to significant performance improvements for networks where $\approx$5 % or more vehicles are part of the VANET.

1.1 Contributions

Initially, the thesis gives an overview of vehicular communications and the potential application areas of VANETs. Afterwards contributions to the topic of self-organizing communication in vehicular ad hoc networks are made in the areas of information dissemination, load control and experimental implementation.

Information Dissemination

The thesis provides evidence that communication over large distances in sparsely connected, highly mobile VANETs is feasible. It presents an evaluation of VANETs by analytic methods and network simulations using detailed vehicular traffic models and real road map data. The achievable speed of information dissemination is approximated and a suitable data dissemination scheme is introduced. By using vehicles on the opposite lane to transport data if no communication partner is in transmission range, information can be distributed in a large area even if only a low number of all vehicles participate in the VANET. Additionally, the thesis introduces a new self-organizing algorithm for generating road status maps based on VANET communication.

Load Control and Utility-Based Self-Organized Scheduling

A new scheduling approach for utility-based packet scheduling and forwarding in VANETs is presented. It allows an efficient and controlled broadcast, avoids overload conditions, guarantees fair bandwidth distribution, and supports multiple applications running simultaneously on a node. A suitable communication architecture providing an application independent implementation of the scheduling is introduced. It includes a store-and-forward module which can forward data at the fair rate even if the respective application is not active at a forwarding node. This can lead to an additional performance improvement for applications that are available only at a subset of all VANET-equipped vehicles.

Experimental Implementation of VANETs

A prototype implementation of the proposed data dissemination techniques and typical VANET applications demonstrates that they can easily be realized on existing hardware. It includes a Self-Organizing Traffic Information System (SOTIS), which can provide traffic information and hazard warnings for a local area of more than 50 km.

1.2 Structure of Thesis

Following this introduction, the next two chapters present background information on vehicular communication. Chapter 2 outlines the fundamentals of vehicular communication by considering communication inside the vehicle, between vehicle and roadside and directly between vehicles. Chapter 3 introduces the concept of a vehicular ad hoc network and establishes basic requirements. It also presents models for the wireless channel and medium access which are used for performance evaluation later on. Typical network topologies of VANETs are outlined and an overview of known data dissemination techniques and related work is given. This background information leads to the system assumptions and the scope of the thesis, presented in Chapter 4.

The main part with own contributions starts with Chapter 5 where communication characteristics of vehicular ad hoc networks are investigated by simple analytical models and approximations. Based on these results, Chapter 6 introduces a novel data dissemination scheme targeted at VANETs. It requires a digital road map onboard the vehicle. An extension of this scheme for generating road status maps independent of commercial map data is presented in Chapter 7.

Chapter 8 covers the aspect of load control and its application-independent implementation. The prototypic implementation of the techniques proposed in this thesis in an experimental system is documented in Chapter 9, which also includes the experimental results. The thesis concludes with a brief summary and outlook.

Apart from the general overview of known data dissemination schemes in Chapter 3, related work for a specific topic is always presented in a separate section of the respective chapter.

Additional information, which is not directly related to the contributions of the thesis but might be helpful to understand the results, is given in the appendix. The network topology in a VANET is mainly determined by the positions and the behavior of individual vehicles. Therefore, Appendix A provides the necessary background information on vehicular traffic models. Appendix B provides details on the GPS model used in the simulations of Chapter 7.

II

Fundamentals of Vehicular Communications

Today's vehicles have become complex electronic networks. Different components constantly exchange the available information and cooperate for the purpose of ensuring driver safety and comfort. Additionally, the vehicle can communicate with the environment by wireless communication. This chapter provides a systematic classification of the various forms of vehicular communication and gives a brief overview of the state-of-the-art and existing standards. It also serves as foundation for the detailed investigation of VANETs in the following chapters.

Based on their specific characteristics, the technologies for vehicular communication can be classified in the following three categories (Figure 2.1):

1. In-vehicle communication
2. Vehicle-to-roadside/vehicle-to-infrastructure communication
3. Inter-vehicle communication (single- and multi-hop)

Although in-vehicle communication is not a focus of this thesis, a brief overview of the technologies in use is included since automotive information systems utilize multiple communication technologies for acquiring, processing and transmitting information (Figure 2.2). Consequently, most applications for VANETs depend on information which is available from the in-vehicle network. For example, the self-organizing traffic information system based on inter-vehicle communication, which is described in detail in Chapter 9, constantly monitors the information from the in-vehicle network: The current velocity and applied brake pressure, which are periodically broadcasted on the in-vehicle communication network, are analyzed in order to characterize the local traffic situation.

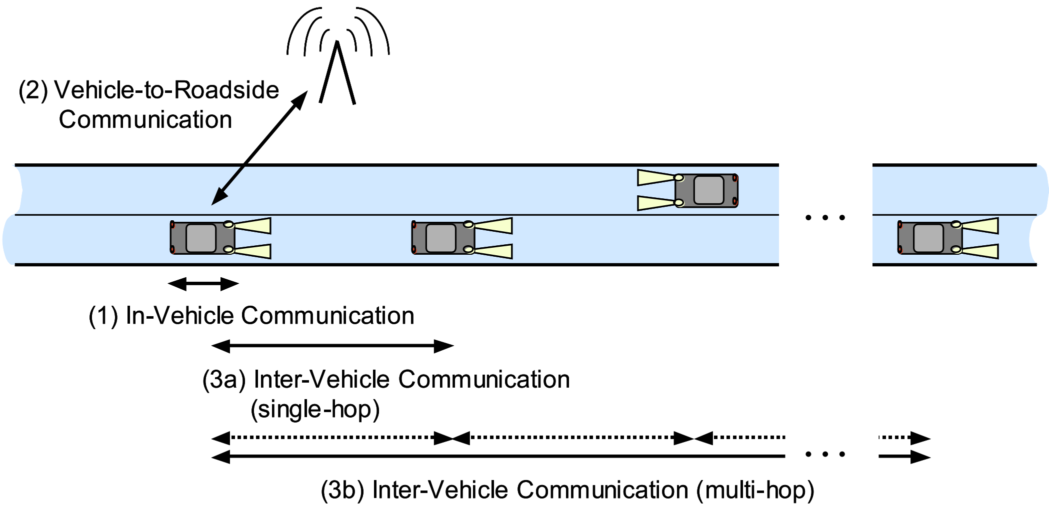


Figure 2.1: Domains of vehicular communication.

2.1 *In-Vehicle Communication*

In-vehicle communication (InVC) enables the information exchange between different components within a vehicle (Figure 2.1(1)) and is widely used in any modern car. In general, two application areas for in-vehicle communication can be distinguished: The first is the in-vehicle network of sensors, actuators and controllers, and the second is high rate multi-media communication for comfort applications, e.g. passenger entertainment.

Since in most cases the number of communicating entities will not change over the lifetime of the vehicle, in-vehicle communication networks have a stable topology, a clearly defined limited set of possible communication partners and rely on wireline communication. Typical are bus and ring topologies. Particularly controller networks have stringent requirements on delay and integrity, whereas in case of comfort applications consequences of violations of the maximum allowed delay or data corruption are less serious but higher data rates are required.

Examples and Standards

With the increasing number of electronic components integrated in vehicles, standardized communication systems for in-vehicle communication became necessary. Currently, the dominant standard in Europe for controller communication in vehi-

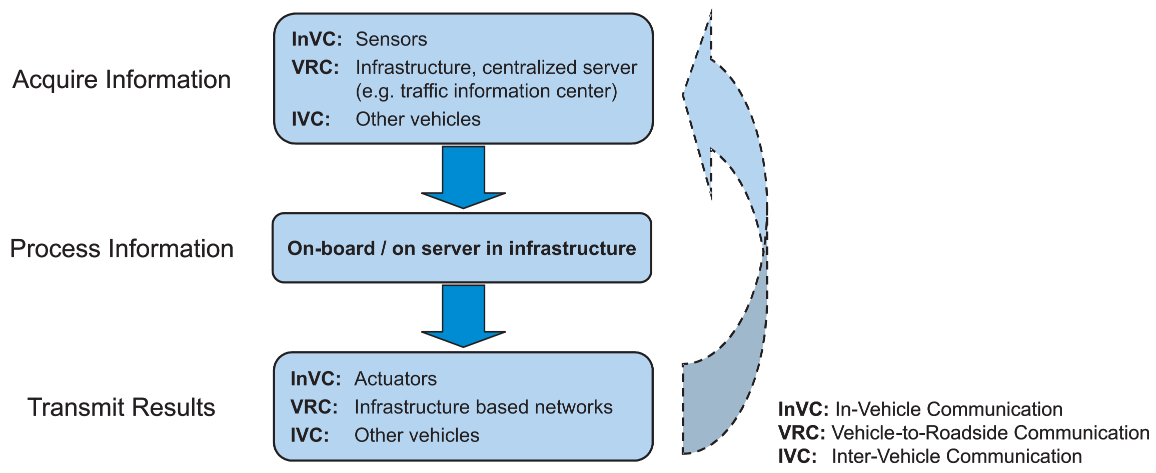


Figure 2.2: Application of communication in automotive information systems.

cles is the Controller Area Network (CAN) [fSI03a]. Two variants of the CAN standard have been specified: The low speed variant [fSI04] handles data rates of up to 125 kBit/s and is mainly used for non-time-critical chassis functions, e.g. switching the headlights on and off. The high speed variant [fSI03b] allows data rates of up to 1 Mbit/s and is used for time-critical systems, such as vehicle stability control. Modern vehicles typically use several CAN busses in order to decouple different functional areas of the vehicle and limit the load on the bus.

For low cost in-vehicle networks, a widely used standard is the Local Interconnect Network (LIN) [Con03] protocol. It provides a simple communication service with a single master and a low data rate ($\leq$ 19.6 kbit/s). Application areas are non-critical systems such as mirror or door control. LIN subnetworks are often connected to CAN networks by a LIN-to-CAN gateway, thereby creating a hierarchical in-vehicle network.

Besides controller communication, the second main application area for in-vehicle communication is passenger entertainment. Because of the required high data rates for multi-media communication – for example for streaming video from an in-vehicle server to a back seat video client – specialized protocols for this application area were developed. Media Oriented Systems Transport (MOST) [Coo04] is an example for such a technology developed by the automotive industry. It offers data rates of up to 150 MBit/s. Furthermore, currently modifications of consumer standards such as IEEE 1394b Automotive or GBit Optical Ethernet for the automotive environment are under discussion.

In-vehicle communication is usually based on wired communication for reliability reasons. An exception is the implementation of the wireless Bluetooth and IEEE 802.11 standards by several vendors of infotainment systems [Var04]. These are used for accessing data on mobile devices such as cell phones and PDAs, e.g. for a hands-free phone system.

2.2 Vehicle-to-Roadside Communication

The term Vehicle-to-Roadside Communication (VRC), also known as vehicle-to-infrastructure communication, is used for any kind of communication from the vehicle to a fixed infrastructure or vice versa (Figure 2.1(2)). This communication can be uni- or bidirectional. Broadcast systems support uni-directional transfer of information from a broadcast station to the vehicle. In contrast, in systems allowing bidirectional communication, the vehicle communicates point-to-point with a base station or access point. In this case, the base station is usually responsible for coordinating the communication, e.g. physical layer synchronization and medium access. Furthermore, the base station can provide access control and avoid excessive load.

Bi-directional VRC technologies can be divided further into cellular mobile phone systems and short range/WLAN-like systems. The former employ the existing cellular infrastructure, e.g. of GMS and UMTS networks, and can provide information wherever the required infrastructure is available. The latter cover only a small local area but can provide high data rates at a low cost.

Depending on the type of air interface and infrastructure, the range in which VRC is possible varies from tens of meters for wireless local area technologies to hundreds of kilometers for public radio systems.

Examples and Standards

A simple form of broadcast systems are public radio stations, e.g. utilizing the FM radio system which allows the transmission of Travel and Traffic Information (TTI) to vehicles via the Traffic Message Channel of the Radio Data System (RDS-TMC) [KM99]. Virtually all middle and high class in-car navigation systems are able to receive TTI via RDS-TMC. Similar services are provided by the Digital Audio Broadcasting (DAB) and the Digital Video Broadcasting Terrestrial (DVB-T) standards. As a matter of principle, these broadcast systems allow only the transmission of information in a single direction: from the fixed infrastructure to the vehicle.

A widely used technology for bi-directional VRC are cellular mobile phone systems, such as GSM/IS-95 and their successors UMTS/cdma2000 [Rap01]. Cellular networks allow access to a wide range of voice and data services, for example TTI and Internet access. For data services, packet-oriented standards such as the General Packet Radio Service (GPRS) are often used. The cellular air interface can either be installed directly in the vehicle or the mobile phone of the driver can be integrated by in-vehicle communication (Section 2.1).

Short and medium range vehicle-to-roadside communication for services such as electronic toll collection, authentication for restricted access roadways and traveler information is provided by the Dedicated Short Range Communication (DSRC) standards. A low rate DSRC standard [AST03a] offering 0.5 Mbit/s was developed in the late 1990s for the 915 MHz band. However, compliant products were never widely accepted. Instead, multiple different proprietary solutions were developed mainly for electronic tolling. Recently, a new DSRC standard in the 5.9 GHz band [AST03b] was adopted which allows data rates of 6-27 Mbit/s. It is the basis for an amendment of the popular IEEE 802.11 WLAN standard [IEE99b, IEE99a] for Wireless Access in Vehicular Environments (WAVE) [IEE]. This standard for vehicle-to-roadside and vehicle-to-vehicle communication is scheduled to be standardized until 2008. Since the IEEE 802.11p/WAVE standard is similar to the IEEE 802.11a standard [IEE99b], it is expected that inexpensive chipsets for vehicle manufacturers and the aftermarket will be available soon after the standard has been adopted.

A novel application area for VRC is the connection of VANETs to existing wireline networks such as the Internet [Bec04]. An access point at the roadside, for example installed at a gas station, serves as a gateway and forwards data packets from the vehicular ad hoc network to the wireline network and vice-versa. Medium range VRC standards, such as WAVE, which additionally support direct communication between vehicles, are advantageous in this case because the same air interface can be used for VRC as well as for inter-vehicle communication.

2.3 Inter-Vehicle Communication

Direct communication between vehicles, so-called Inter-Vehicle Communication (IVC)[1], allows information exchange without requiring any fixed infrastructure. While a similar form of communication has recently been deployed on a large scale in maritime traffic with the Automatic Identification System (AIS) [Har00, AKR99] and in aeronautics with the Automatic Dependant Surveillance - Broadcast (ADS-B) [AKR99, ZS03, Ras01] system, it is not yet in wide use in the automotive sector.

A basic requirement for any kind of IVC is an air interface capable of ad hoc communication: In contrast to VRC, synchronization and medium access cannot be coordinated by a base station. The network has to be self-organized and allow spontaneous peer-to-peer communication between any two vehicles which are within mutual transmission range. Thus, medium access and synchronization have to be solved in a decentralized way [EWR04, EWR+05, Ebn05b].

Two types of IVC can be distinguished based on the relative positions of information source and destination:

Single-hop: In single-hop IVC (Figure 2.1(3a)), information source and destination are within transmission range of each other and communicate directly.

Multi-hop: Information exchange over distances larger than the transmission range of a single vehicle can be achieved using multi-hop IVC (Figure 2.1(3b)). Information source and destination are connected by one or more intermediate vehicles which forward the information.

IVC is the foundation for vehicular ad hoc networks, which allow a wide range of applications in the areas comfort and safety. One objective of this thesis is to present a new VANET design achieving a large range in which information is exchanged without classical multi-hop communication. Therefore, applications, characteristics and requirements of VANETs are presented in detail in a separate chapter (Chapter 3).

Examples and Standards

In the automotive sector, there is not yet an established and wide spread standard for IVC. Studies have shown that for some comfort applications, even conventional

[1] also known as Car-to-Car Communication (C2CC)

IEEE 802.11b WLAN is suitable [OK04]. Although developed for a low mobility office environment, it can cope with high relative velocities in line-of-sight situations. Measurements show that a transmission range of more than 250 m can be achieved in typical IVC scenarios with standard WLAN in the 2.4 GHz ISM band and an omnidirectional roof antenna. E.g., in [SBSC02, GG05] a range of more than 400 m is reported for rural environments and in [GMRL05] a communication time of ≈ 7 s is observed in a highway scenario for two vehicles with a relative velocity of 400 km/h.

However for a large scale deployment of IVC, a standard developed specifically for automotive applications may be advantageous. Taking the characteristics of the vehicular environment into account, a larger transmission range and a lower delay for critical applications can be achieved. In order to avoid the installation of an additional dedicated air interface, a single standard for IVC and VRC is favorable. Several standards developed for (medium range) VRC (see Section 2.2) include support for IVC. For example, the IEEE 802.11p standard dedicates specific channels to IVC and is suitable for IVC based ad hoc networks [TMJH04].

An alternative approach is the extension of existing cellular standards to support ad hoc communication. For example, a modification of the UMTS Terrestrial Radio Access (UTRA) Time Division Multiple Access (TDMA) standard, called UTRA TDD Ad Hoc [LEM$^+$04, ERW$^+$03], has been recently proposed. Combined approaches allowing ad hoc and cellular operation simultaneously are also feasible [Ebn05c].

2.4 Comparison of Characteristics

Table 2.1 compares the different types of vehicular communication. It illustrates that the application areas for VRC and IVC partly overlap: Some services, such as traffic information and hazard warnings, can be implemented either based on VRC or IVC.

Compared to VRC, IVC has the following advantages:

No infrastructure: IVC does not require any fixed infrastructure and therefore does not require a specific service provider. Communication is possible whenever a vehicle equipped with the communication system is within the transmission range of the air interface.

No service charges: Since the network is provided by the vehicles themselves, communication is available without any service fees.

Low delay for single-hop: For single-hop communication, IVC is possible with a significantly lower delay (<50 ms) than VRC, which is particularly important for emergency warning services.

However, IVC faces two main challenges which are not present for VRC:

Market introduction/network availability: Whereas cellular communication and uni-directional VRC broadcast technologies are already deployed and provide large coverage, IVC is a relatively new technology. Communication is only possible, if another vehicle equipped with the IVC system is within transmission range. Therefore, the system can only provide significant benefit if a minimum number of vehicles is equipped. Furthermore, for IVC the availability of the network or a specific maximum delay cannot be guaranteed. In particular in case of low market penetration, this limits the type of possible applications to those that tolerate an unreliable communication with varying delay.

High delay for multi-hop: If information is to be disseminated over very large distances, the delay of IVC increases due to the large number of intermediate hops. Cellular systems can use a fast wireline backbone network to forward the information and are therefore able to achieve a lower delay in this case.

Therefore, the advantages and disadvantages of both forms of communication need to be considered depending on the particular service. It can also be very advantageous to combine both techniques, e.g. using IVC to acquire information for a local area of 50-100 km and VRC for wider ranges.

Table 2.1: Forms of vehicular communications.

	Typical Standards	**Typical Data Rate**	**Example Applications**	**Range of Information Dissemination**
IN-VEHICLE (controller networks)	CAN, LIN, byteflight, FlexRay	10 kbit/s – 10 Mbit/s	communication of in-vehicle electronic units: wheel speed sensor to navigation system, steering column to headlights	0 – 10 m (in-vehicle)
IN-VEHICLE (multi-media)	MOST, IEEE 1394b Automotive	20 – 1000 Mbit/s	video and audio streaming to the back seat, rear vision camera	0 – 10 m (in-vehicle)
VEHICLE-INFRASTRUCTURE (short range, bi-directional)	DSRC, IEEE 802.11p/WAVE	0.5 Mbit/s – 27 Mbit/s	electronic tolling, emergency vehicle signal priority, work zone warning	1 – 500 m
VEHICLE-INFRASTRUCTURE (long range, uni-directional)	RDS/FM radio, DAB, DVB-T	80 bit/s – 8 Mbit/s	traffic information, audio/video broadcast	1 m – 100 km
VEHICLE-INFRASTRUCTURE (long range, bi-directional)	cellular mobile phone systems: GSM, GPRS, IS-95, UMTS, cdma2000	9.6 kbit/s – 2Mbit/s	Internet access, (video) telephony	1 m – 100 km
INTER-VEHICLE (single-hop)	DSRC, IEEE 802.11p/WAVE	0.5 – 27 Mbit/s	platooning, emergency warning system, cooperative adaptive cruise control	1 - 1000 m
INTER-VEHICLE (multi-hop)	DSRC, IEEE 802.11p/WAVE, forwarding not yet standardized	0.5 – 27 Mbit/s	traffic information and management, hazard warning, coverage extension for roadside APs	1 m – 100 km

III

Vehicular Ad Hoc Networks

This chapter introduces the concept of a Vehicular Ad Hoc Network (VANET) for safety and comfort applications. A VANET is a specific kind of wireless packet switching network. The different steps which led to the development of VANETs are briefly presented in the following. Afterwards, applications and characteristics of VANETs are considered. In addition, the required background information on medium access techniques and models for the wireless channel are given. Typical VANET topologies are characterized. The chapter concludes with an overview of known data dissemination schemes for VANETs.

3.1 Evolution of Mobile to Vehicular Ad Hoc Networks

In packet switched networks, instead of setting up a dedicated connection, data packets from multiple users are transmitted on a single link. Early research on wireless packet switched networks began in the early 1970s with the development of a simple scheme for radio channel access, the ALOHA protocol [Abr70, Abr85], at the University of Hawaii. A completely connected ground network of stationary terminals was assumed. The direction of communication was always from a terminal to the computer center or vice-versa – direct station-to-station communication was not allowed [Tan88].

The assumption of stationary terminals was dropped in mobile packet radio networks, which consider the mobility of users [SG85]. However, these networks still distinguish between a mobile terminal (source or sink for information flow) and a repeater (extending the communication range by repeating data transmissions). Repeaters are therefore a form of infrastructure required by the network.

In a Mobile Ad Hoc Network (MANET) [MMe04], each terminal is a potential information source and acts simultaneously as a mobile router which forwards data packets received from other nodes, as illustrated in Figure 3.1. Therefore, communication over distances much larger than the transmission range of an individual node is possible without requiring any infrastructure such as dedicated routers or repeaters. For example, Nodes A and C in Figure 3.1 are able to communicate via Node B despite being separated by more than the transmission range.

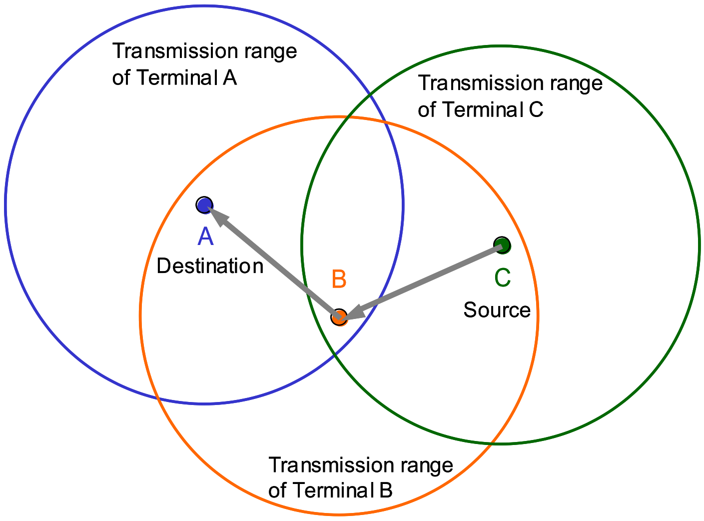


Figure 3.1: Communication in a MANET.

A Vehicular Ad Hoc Network (VANET) is the application of the MANET approach for communication between vehicles: Vehicles communicate by IVC (Chapter 2.3) and, as in a MANET, each vehicle also forwards information received from other vehicles nearby (Figure 3.2). Here, the term 'information forwarding' is used instead of 'packet forwarding', since – as discussed in Section 3.7 – packets can also be processed and modified at intermediate nodes. This approach is very common in ad hoc sensor networks [ASSC02] and VANETs, whereas in classic MANETs packets are forwarded without any modification of the payload.

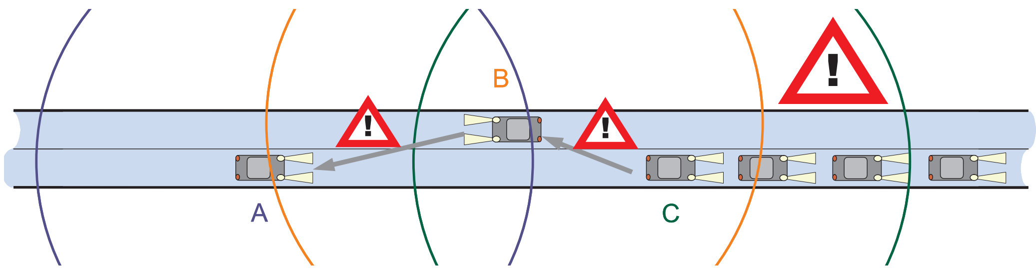


Figure 3.2: Hazard warning in a vehicular ad hoc network.

Additionally, information can be stored and *transported physically on-board* the vehicle. Due to the specific movement pattern of vehicles on roads, this form of physical transport is more effective than in an usual MANET and can contribute significantly to achieving a large range in which information can be disseminated.

3.2 Applications

A large number of vehicular information and driver assistance systems can benefit from VANET technologies: The reason is that these systems usually rely on information on the local (traffic) situation which can be obtained using sensors such as radar or lidar. However, sensors installed at an individual vehicle are limited to the local neighborhood, e.g. within a range of 10-100 meters, and can be obstructed by vehicles ahead. In a VANET, vehicles complement the local sensor data with sensor data received from other vehicles [LH04]. Thus, the range in which a driver assistance system acquires information is extended to multiple kilometers (Figure 3.3).

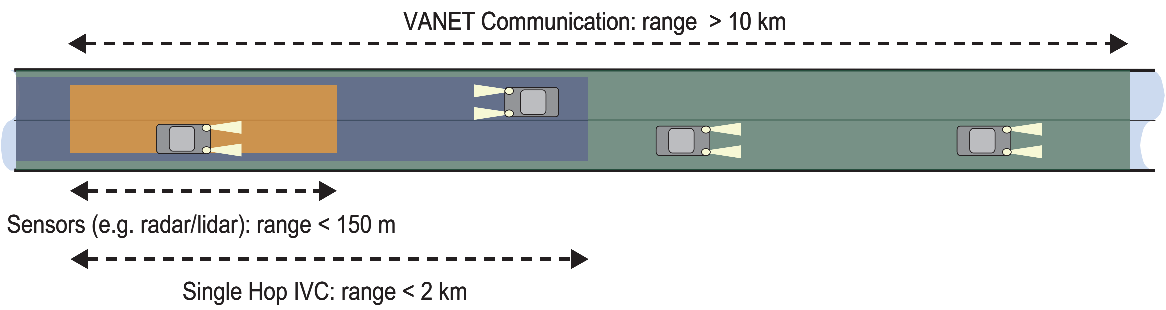


Figure 3.3: Maximum ranges in which driver assistance systems can acquire information with on-board sensors and/or communication.

Furthermore, the specific properties of a VANET allow the deployment of a wide range of new attractive services which are either not feasible or not cost-effective with other technologies.

Applications for VANETs can be divided into two classes: safety applications and comfort applications. Comfort applications improve passenger comfort and traffic efficiency. Examples for services in this category are:

- traffic information [GIO04, WER+03b] for dynamic route updates, depending on existing obstructions of traffic (e.g. by construction or traffic jams),

- weather information (temperature and road condition),
- enhanced Adaptive Cruise Control (ACC) systems which augment the information of the on-board (radar or lidar) sensors with information received via the VANET,
- roadside advertising/marketing (in combination with access points at the roadside) [EWER03, NDZ+05] and services providing travel information such as tourist, gas station or restaurant information (location and price),
- and entertainment services such as chatting, gaming, music download [NDP+05] or extending the coverage of Internet access [Bec04].

Services such as continuously updated traffic or weather information generate significant amounts of data traffic, while most users are not willing to spend much for these kinds of services. Therefore, the main advantage of VANETs compared to infrastructure based communication for applications in this category is the avoidance of service charges for communication since no service provider is required.

The second main category of applications, safety applications, increases the safety of passengers by exchanging driving related information in the VANET. By VANET communication, the range in which a safety system is aware of the local situation is strongly extended. The systems monitor the local driving situation and in case a hazard is detected, this information is either presented to the driver or used to activate an actuator of an active safety system. Example applications of this class are:

- hazard and emergency warning system [ER01, CS02, XMS04, TMJH04],
- cooperative collision avoidance [BTD06],
- lane-changing assistant, intersection coordination [SX04],
- driver assistance systems, e.g. for overtaking, lane merging,
- traffic sign/signal violation warning, and road-condition warning.

Applications of this class usually demand direct information exchange from vehicle to vehicle due to the stringent delay requirements.

Compared to comfort applications, safety applications have stronger requirements on reliability and integrity of communication. Since VANETs are based on IVC, the extend to which communication is possible depends on the number of vehicles equipped with an IVC system (Section 2.4). Safety applications usually assume that at least one vehicle involved in the critical situation disseminates an emergency notification in the VANET. Therefore and due to their stringent requirements on reliability and delay, safety applications solely based on IVC will not be feasible until a relatively large fraction of vehicles is equipped with an IVC system [LÖ05]. For example, it is expected that a market penetration of at least 10% is required until safety applications such as local hazard warning will have a noticeable positive effect for the user [SMM+05].

3.3 Characteristics and Requirements

VANETs differ from conventional fixed and mobile data networks in many aspects. The differences are so severe that many existing network protocols and communication paradigms cannot be applied, which will be discussed in detail in Section 3.7. But first, the general characteristics of VANETs will be considered.

Most challenges in VANETs are related to the high mobility of the nodes, since relative velocities of up to 400 km/h may occur on highways. High mobility leads to a rapidly changing network topology with extremely short path lifetimes. However, due to the fact that in general vehicles move on roads, topology changes are somewhat predictable.

This fact can be exploited, e.g. by using digital road maps to aid the communication [LMFH05] or by only considering vehicles travelling in the same direction, which reduces the rate of topology changes [BEH04] but also halves the number of available communication partners. For example, in a typical highway scenario, the average link lifetime for links to vehicles driving in the opposite direction is lower than 5 s if a radio range of 160 m is assumed. In contrast, the average link lifetime to vehicles driving in the same direction is larger than 50 s for the same scenario [BEH04].

Since VANETs employ direct information exchange without any infrastructure, a basic requirement is ad hoc inter-vehicle communication. The given high mobility situation leads to a highly time-variant mobile radio channel. Thus, suitable physical and medium access layers are needed which can perform communication with sufficient reliability.

As mentioned in the introduction, the question of market introduction is of particular importance for vehicular ad hoc communication, since it is a technology with network effects [SMM+05]: The value for the user depends on market penetration. A higher penetration means more benefit and more possible applications for the user. In contrast, low penetration leads to a sparsely connected network, where most of the time no communication partner is in range [Ebn05a, BEH04]. Thus, on the one hand, the deployed technologies must be able to cope with situations with a very low density of nodes, on the other hand, scalability must be achieved so that the system also works in situations with high node densities, e.g. in a traffic jam situation where every vehicle is equipped with the communication system.

Another characteristic property of a VANET is in the relation of information source to destination. While the dominant form of communication in the wireline Internet and conventional MANETs is unicast end-to-end communication, a typical example being the client access of data at a HTTP server, in VANETs the dominant form of communication is broadcast within a specific geographic region (geocast): Most applications in VANETs aim to provide information on the local neighborhood, which has been sensed by vehicles in the local area. Since the specific addresses of the potential communication partners are unknown and irrelevant, a form of broadcast is usually applied [WER05a, Mic01, KEOO04]. Furthermore, if a low market penetration of only 2-10% is assumed for the considered inter-vehicle communication system, the broadcast based data dissemination approaches can distribute the relevant information in an extremely large area – orders of magnitude larger than conventional network routing based approaches [WER05a]. A disadvantage of using broadcast, however, is that common approaches for congestion control are hard to apply.

Security in vehicular ad hoc networks is also an important topic, particularly in case of safety applications. Legitimacy and privacy need to be guaranteed – even under real-time constraints. This issue has been addressed by several authors in the recent past and possible solutions have been proposed, e.g. in [RH05, Sch05]. A different approach that can be applied for most comfort applications is to use the high level of redundancy in a VANET. An event is typically detected by several vehicles, therefore a vehicle can detect a potentially erroneous message by comparing it with information received from nearby vehicles. Reputation systems spread this additional knowledge by disseminating not only the data itself but also its level of credibility (an example is the VANET reputation system in [DFM05]).

Despite these challenges, some conditions are also relaxed in VANETs. Energy, computational power and memory are not as restricted as in a MANET or sensor network [LMZ+06] and allow more complex data dissemination protocols. Table 3.1 summarizes the comparison of a VANET with conventional mobile ad hoc networks and the wireline Internet.

Table 3.1: Comparison of VANETs with MANETs and the wireline Internet.

	Mobility	**Energy**	**Computational Power**	**Communication Type**	**Congestion Control**
VANET	high	unlimited	high	geocast, broadcast	open issue
MANET	low	limited	medium	unicast	end-to-end
Wireline Internet	none	unlimited	high	unicast	end-to-end

3.3.1 Scalability

As mentioned, an important requirement for proposed VANET mechanisms is scalability. A heavily cited proof presented in [GK00] by Gupta and Kumar states for an ad hoc wireless network consisting of N nodes that the obtainable data rate per source-destination pair decreases approximately by $1/\sqrt{N}$. This result holds even if optimal selection of transmission ranges and traffic pattern is assumed.

However, the ad hoc network considered in [GK00] is fixed and does not take mobility of the individual nodes into account. Its model for capacity calculation is applied to a *mobile* ad hoc network in a follow-up paper by Grossglauser and Tse [GT02] with the result that mobility increases the capacity. For a random mobile ad hoc network without delay constraints, the data rate per source-destination pair can be kept constant even as N increases.

Furthermore, most VANET applications do not require individual source-destination communication but instead can use a local broadcast of their current information to inform all vehicles in range. Vehicles sensing identical information do not need to transmit any data.

A scalable VANET scheme should thus take advantage of the regular mobility pattern and avoid individual source-destination communication (unicast).

3.4 Wireless Channel

In any wireless communication system, the wireless channel between transmitter and receiver imposes fundamental limitations. Radio channel modeling for various propagation environments with a sufficient grade of accuracy is therefore a demanding task. Commonly, the modeling is divided into two parts:

Large-scale propagation models predict the mean received power at a given distance from the transmitter.

Small-scale propagation (fast fading) models consider the (random) variations of the received signal near a local position. These are mainly due to multipath propagation and cause the received power to differ by as much as 4 orders of magnitude even if the receiver is only moved by a fraction of the wavelength [Rap01].

In this section, a brief introduction to commonly used propagation models is given in order to provide the necessary background for the simulative performance evaluation in this thesis. A more detailed introduction to wireless channel modeling can be found in [Rap01, HM05]. In the following, the nomenclature of [Rap01] is used.

3.4.1 Free-Space Model

The free space equation predicts a quadratic decrease of the received power with the distance d between transmitter and receiver. It is applicable if there is a single Line-Of-Sight (LOS) path only.

$$P_\mathrm{r}(d) = \frac{P_\mathrm{t} G_\mathrm{t} G_\mathrm{r} \lambda^2}{(4\pi)^2 d^2 L} \tag{3-1}$$

$$= P_\mathrm{r}(d_0) \cdot \left(\frac{d_0}{d}\right)^2, \quad d \geq d_0 \geq d_\mathrm{f} \tag{3-2}$$

P_t and P_r are the transmitted and the received power, G_t and G_r are the respective antenna gains and L is the system loss factor. Parameter λ describes the wavelength

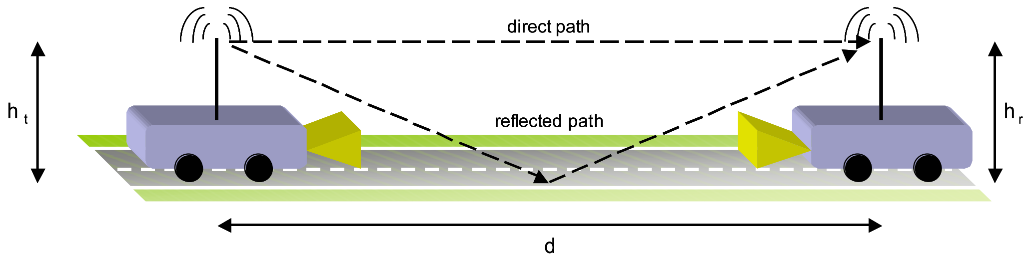


Figure 3.4: Two-ray propagation model.

of the considered wireless communication system. The distance d_0 is the receive power reference point, which is a point beyond the far-field distance. The far field distance d_f, also known as Fraunhofer distance, can be calculated as $d_\mathrm{f} = \frac{2D^2}{\lambda}$. D characterizes the largest physical linear dimension of the antenna. Additionally, d_f has to exceed λ and D to be in the far-field region.

Neglecting the system loss with $L = 1$, the corresponding large-scale path loss $\overline{PL}$ in dB is given by

$$\begin{aligned}\overline{PL}(\mathrm{dB}) &= 10\log\frac{P_\mathrm{t}}{P_\mathrm{r}(d)} = -10\log\left[\frac{G_\mathrm{t}G_\mathrm{r}\lambda^2}{(4\pi)^2 d^2}\right] \\ &= 20\log d - \left(10\log G_\mathrm{t} + 10\log G_\mathrm{r} + 10\log\left[\frac{\lambda^2}{(4\pi)^2}\right]\right) \qquad (3\text{-}3)\end{aligned}$$

3.4.2 Two-Ray Model

The so-called ground reflection or two-ray model is a simple large-scale path loss model which considers the ground reflection in addition to the direct path (Figure 3.4). The superposition of the two paths results in a much higher path loss than the free-space model – the received power $P_\mathrm{r}(d)$ can be approximated by

$$P_\mathrm{r}(d) = \frac{P_\mathrm{t}G_\mathrm{t}G_\mathrm{r}h_\mathrm{t}^2h_\mathrm{r}^2}{d^4} \qquad (3\text{-}4)$$

if d exceeds the cross-over distance $(4\pi h_\mathrm{t}h_\mathrm{r})/\lambda$, otherwise free-space propagation is assumed. Height of transmitter and receiver are represented by h_t and h_r, respectively. The resulting large-scale path loss $\overline{PL}$ in dB can be written as

$$\overline{PL}(\mathrm{dB}) = 40\log d - (10\log G_\mathrm{t} + 10\log G_\mathrm{r} + 20\log h_\mathrm{t} + 20\log h_\mathrm{r}) \qquad (3\text{-}5)$$

The two-ray model is widely used in the simulation of wireless networks. It is suitable for predicting the average received power in LOS (i.e. non-crowded) vehicular communication situations [ZSO+05] since the ground reflection plays an important role in inter-vehicle communication [Mau05].

3.4.3 Log-Distance Path Loss Model

A generalization of the free space model is the log-distance path loss model. It is based on the observation that received power decreases logarithmically with distance, and considers different propagation environments by adapting the *path loss exponent* n.

$$\overline{PL}(\mathrm{dB}) = \overline{PL}(d_0) + 10n \log\left(\frac{d}{d_0}\right) \tag{3-6}$$

For the free space model, the exponent n is set to $n = 2$. In vehicular communication scenarios, path loss exponents from 1.4 to 3.5 and from 2.8 to 5.9 have been reported in LOS and NLOS situations, respectively [YEY+04].

3.4.4 Log-Normal Shadowing Model

The previously presented models calculate the average received power deterministically based on the distance d between receiver and transmitter. However, the received power in a specific situation and instance in time may differ significantly from this predicted average value due to the current local propagation and shadowing situation. The received power can therefore be seen as a random variable with expected value $\overline{PL}$.

It has been shown that the random received power PL is usually distributed log-normally. Due to this observation, the log-normal shadowing model calculates the instantaneous PL by adding a Gaussian distributed random variable X (in dB) with zero mean and standard deviation σ as shown in Equation 3-7.

$$PL(\mathrm{dB}) = \overline{PL}(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X(\mathrm{dB}) \tag{3-7}$$

A LOS situation usually leads to a lower standard deviation σ than a NLOS situation. Inter-vehicle measurements in the 5 GHz Band show a good agreement of the average attenuation with the log-normal model in LOS and NLOS scenarios [Mau05]. In general, for the simulation of vehicular communication scenarios, the value of σ is often assumed to be in the range of 4 to 12 dB. Figure 3.5 illustrates the path loss for the various large-scale propagation models.

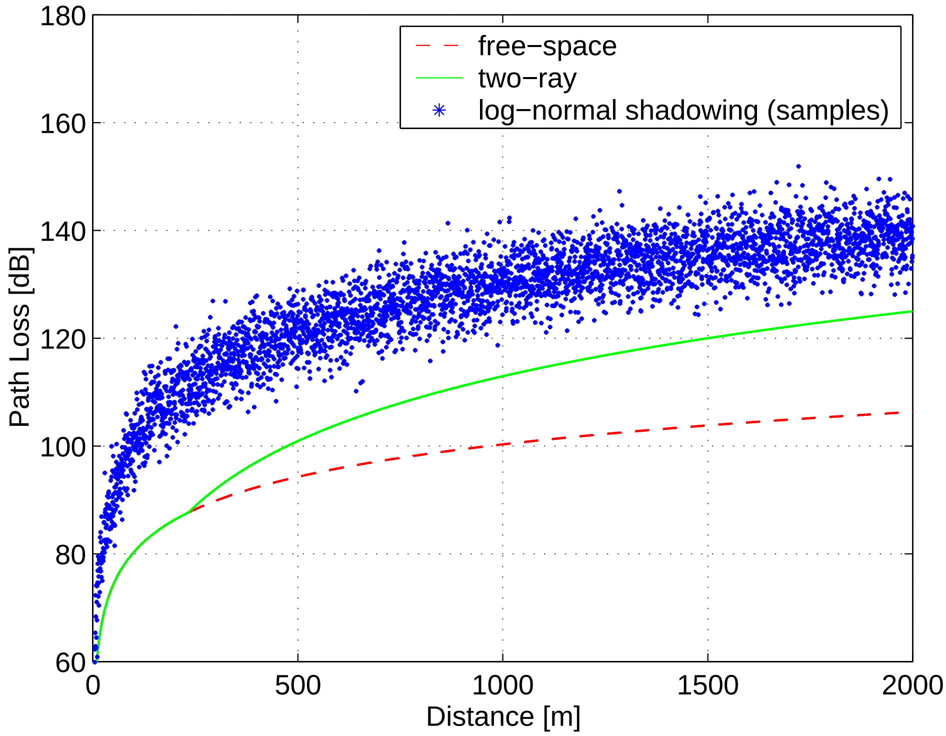


Figure 3.5: Comparison of path loss for the free-space, two-ray and log-normal shadowing models. (2.4 GHz ISM band, $\lambda = 12.1\,\text{cm}$, two-ray: $h_\text{t} = h_\text{r} = 1.5\,\text{m}$, log-normal shadowing: path loss exponent $n = 3$, $\sigma = 4\,\text{dB}$)

3.4.5 Fast Fading Models

In addition to the slow changes of the mean received signal power over larger distances predicted by the large-scale propagation models, multipath effects can lead to a rapid variation of the received signal power about the median value. Fast fading models consider this influence of multipath propagation on the received signal.

The transmitted signal is influenced by reflecting objects and scatterers. Depending on the length of a specific (reflected) path from transmitter to receiver, the propagation delay varies. Mobility of the transmitter and receiver, as in the case of vehicle to vehicle communication, causes a Doppler shift of the signals that depends on the respective angle of arrival. Thus, the received signal is a superposition of differently attenuated, delayed and Doppler-shifted versions of the transmitted signal. The interference of the different versions can be constructive or destructive. Since small differences in path length can lead to large differences in phase of the superimposed path signals, mobility causes a strong and fast variation of the received signal which is consequently termed fast fading.

In addition to the time-variant characteristics of the radio channel due to mobility, multipath propagation can lead to a frequency-dependent attenuation of the signal. If the duration of a transmitted symbol is smaller than the maximum channel tap delay, the channel becomes frequency-selective: Within the signal bandwidth, some frequencies are attenuated significantly more than others.

A measure for the time-varying nature of the channel is the *coherence time* T_C. It is the time span in which only a marginal change of the channel occurs. A simple approximation for T_C is the reciprocal of the maximum Doppler frequency $f_{D,max}$ for the channel.

$$T_C \approx \frac{1}{f_{D,max}} \tag{3-8}$$

Analogously, the frequency-selectivity is characterized by the *coherence bandwidth* B_C which can be approximated by the reciprocal of the maximum delay difference between the received signal versions (maximum channel tap delay τ_{max}).

$$B_C \approx \frac{1}{\tau_{max}} \tag{3-9}$$

The effect of fast fading on the received signal is often represented by a random process. For situations where all paths are similar, the received envelope of the signal is commonly modeled by a Rayleigh distribution. If a dominant propagation path exists, e.g. in a line-of-sight situation, the resulting distribution is Ricean [Pap91]. Its parameter K is called the Ricean factor and calculated as the ratio of the power of the dominant path to the power in the other paths. With $K \rightarrow 0$, it is equal to the Rayleigh distribution. Another generalization of the Rayleigh distribution is the Nakagami-m distribution which has an additional parameter, the Nakagami fading parameter m that controls the tail distribution. With $m = 1$, it corresponds to the Rayleigh distribution. Parameter values for both distributions obtained by inter-vehicle communication measurements can be found in [Mau05, TJM+04]. More detailed models for multipath fading channels additionally take higher order statistics into account [Pro01, Rap01].

Fast fading has a strong influence on the design of a suitable physical layer for vehicular ad hoc communication. For example, in a system performing channel estimation using a preamble at the beginning of each data packet such as IEEE 802.11p, the coherence time determines the maximum packet size on the physical layer. Likewise, since the IEEE 802.11p proposal is based on Orthogonal Frequency Division Multiplexing (OFDM), the coherence bandwidth determines the allowed subcarrier spacing [ZSO+05]. Efficient modulation and coding techniques can partly mitigate the effects of fast fading so that the impact on higher layers is minimized.

3.5 Medium Access Control

In a wireless network, the wireless channel needs to be shared by all nodes within a local area. Therefore, the access to the wireless medium has to be coordinated so that the data transmitted by an individual user is not corrupted by the transmission of another. In general, users of a wireless communication system can be separated

- in time (Time Division Multiple Access, TDMA),
- in frequency (Frequency Division Multiple Access, FDMA),
- in space (Space Division Multiple Access, SDMA) and
- in code (Code Division Multiple Access, CDMA).

In a vehicular ad hoc network, usually TDMA is applied since the other multiple access methods have to cope with the following difficulties in a VANET scenario: In a single carrier system, the receiver can only listen to one frequency at a time. FDMA requires therefore a coordination which user is active (transmitting or receiving) at which frequency. Because of the rapidly changing topology in a VANET, this coordination is very challenging. However, decentralized combined FDMA+TDMA methods have been proposed, e.g. to exploit multiple frequency channels of the proposed IEEE 802.11p standard [LMH04].

SDMA, which uses directional antennas to separate the users, is not reasonable in case a vehicle wants to transmit to all other vehicles in the local area – which is assumed to be the dominant form of communication in VANETs. CDMA suffers from the well-known near-far effect (power-impairment problem [LEM+04]) meaning that a near simultaneous transmission may impede the detection of a code used by a vehicle farther away. While in cellular systems this near-far effect can be compensated by power control schemes, these cannot be applied in VANETs. The reason is that since communication occurs in a decentralized ad-hoc fashion and is dominated by broadcast, neither a central station nor a specific receiver, for which the power level can be adjusted, exist.

For TDMA systems, a wide range of medium access protocols has been proposed. The simplest, the ALOHA protocol [Abr70, Abr85], does not use any coordination at all. A node transmits whenever it has data to send. An improved variant, slotted ALOHA, doubles the achievable data rate by assuming that the nodes are synchronized in time and start transmissions only at specific instances in time (so-called slots). Reservation based ALOHA protocols (R-ALOHA) use an even higher degree of coordination and reserve resources in advance so that collisions can be nearly completely avoided. For vehicular ad hoc networks, several R-ALOHA variants have been proposed [Ver97, Ann99, LHSR01, Ebn05a].

A different approach is taken by the Carrier-Sense Multiple Access (CSMA) protocol which is, e.g., applied in the Distributed Coordination Function (DCF) of the IEEE 802.11 standards. In CSMA, each node monitors the status of the wireless channel prior to a transmission. If signal power exceeding the *carrier-sense threshold* is detected, the medium is assumed to be busy and the transmitter defers its transmission. IEEE 802.11 implements CSMA with Collision Avoidance (CA) and binary exponential backoff [IEE99a]: In case of detecting a busy medium, the node chooses a uniformly distributed random number within a range termed the *contention window*. It determines the time which a station has to wait after detecting an idle medium before it is allowed to start its transmission. With every attempt to transmit that is deferred and every unsuccessful transmission, the contention window is doubled until a maximum value is reached. Transmission failures are detected by not receiving an acknowledgement for a transmitted unicast frame. Upon successfully transmitting a packet, the contention window is reset to its minimum value. A detailed evaluation of TDMA medium access protocols for vehicular ad hoc networks can be found in [Ebn05a].

3.6 Network Topology

Within a VANET, the degree of connectivity is mainly determined by the number of vehicles equipped with the ad hoc communication system which are in transmission range. The expected value $\overline{N}_{\mathrm{TX}}$ of the number of ad hoc capable vehicles within transmission range R is therefore used as an indicator for the connectivity of the VANET.

$$\overline{N}_{\mathrm{TX}} = 2N_{\mathrm{L}}\gamma\rho R = 2\kappa R \tag{3-10}$$

The product $\gamma\rho$ is the density of *equipped* vehicles (in veh/km/lane), N_{L} is the number of lanes.

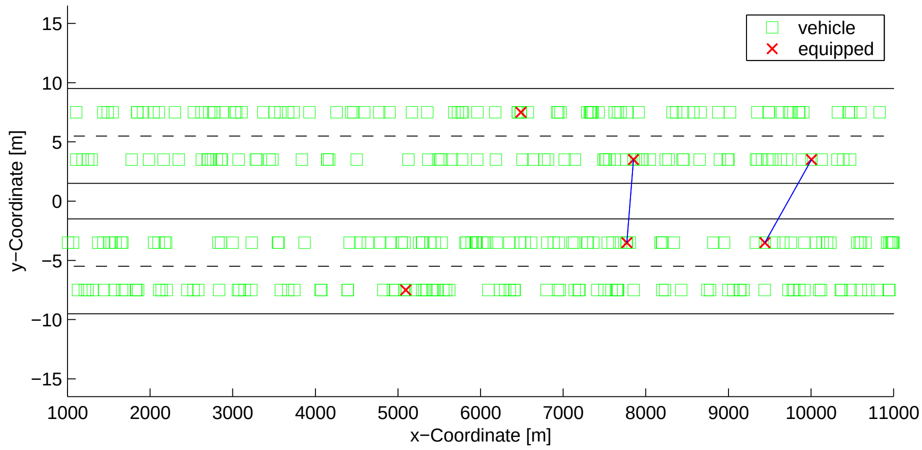
Depending on $\overline{N}_{\mathrm{TX}}$, VANETs exhibit different properties regarding data dissemination. In this thesis, a VANET with $\overline{N}_{\mathrm{TX}} \in (0.0, 5.0]$ is classified as a *sparsely connected VANET*. A network with $\overline{N}_{\mathrm{TX}} \in [10.0, \infty)$ is analogously termed a *dense VANET*. VANETs with a value of $\overline{N}_{\mathrm{TX}}$ between approx. 5.0 to 10.0 can show the characteristics of both classes, depending on the particular network scenario.

3.6.1 Sparsely Connected VANETs

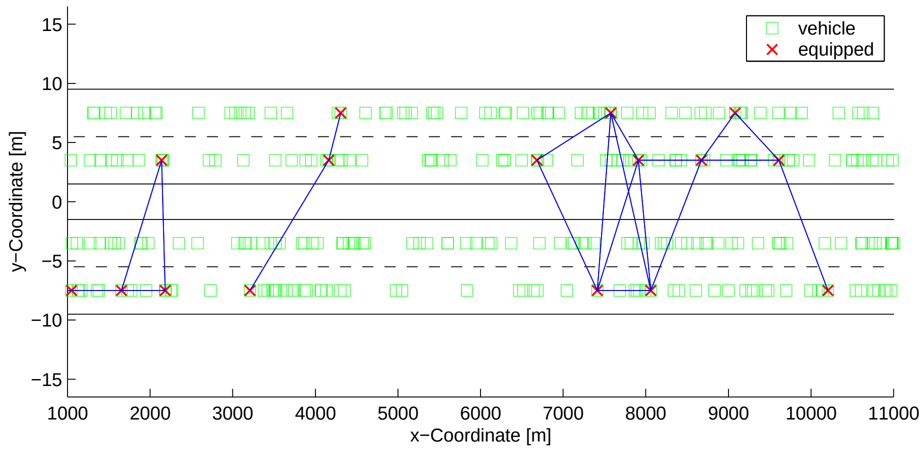
A VANET is sparsely connected if either only a small number of all vehicles is equipped with the communication system or the road traffic density in general is low. Figure 3.6 illustrates the resulting network topology on a 10 km 2x2 highway segment for a traffic scenario with a road traffic density of $\rho = 7.5\,\mathrm{veh/km/lane}$ if the penetration γ is varied. Vehicles are indicated by a square, vehicles equipped with the ad hoc communication system are additionally marked by a cross. Possible communication links are shown as a line connecting the respective nodes. For the sake of clarity, different scales are used for x- and y-coordinates, respectively, and vehicle symbols are enlarged.

In case of low values of $\overline{N}_{\mathrm{TX}}$ (i.e. a low market penetration of the ad hoc system), only occasional communication with a vehicle on the opposite lane is possible, as shown in 3.6(a). Connected segments involving multiple hops almost never occur, as expected from the discussion in Section 5.1.1. When γ is increased to 0.05 in 3.6(b), the network is often partially connected in a range of 2-3 hops but still heavily fragmented.

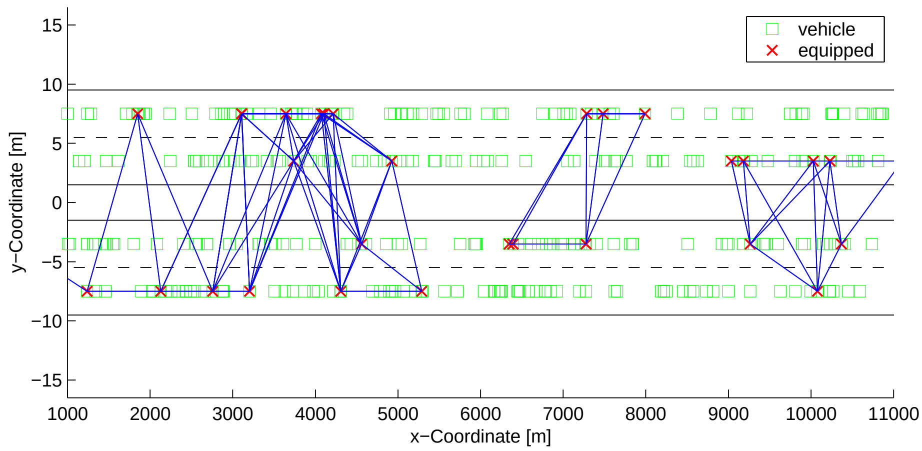
As a conclusion, for sparsely connected VANETs, multi-hop routing approaches are not suitable – the network is simply not connected in ranges of multiple hops. Information can only be disseminated in a large information range, if vehicles on the opposite lane physically transport the information on board and are used to close the gaps between fragmented networks. (Note that this kind of information dissemination occurs only in direction opposite to the direction of movement of a vehicle.)



(a) 2% equipped ($\overline{N}_{\mathrm{TX}} = 1.2$)

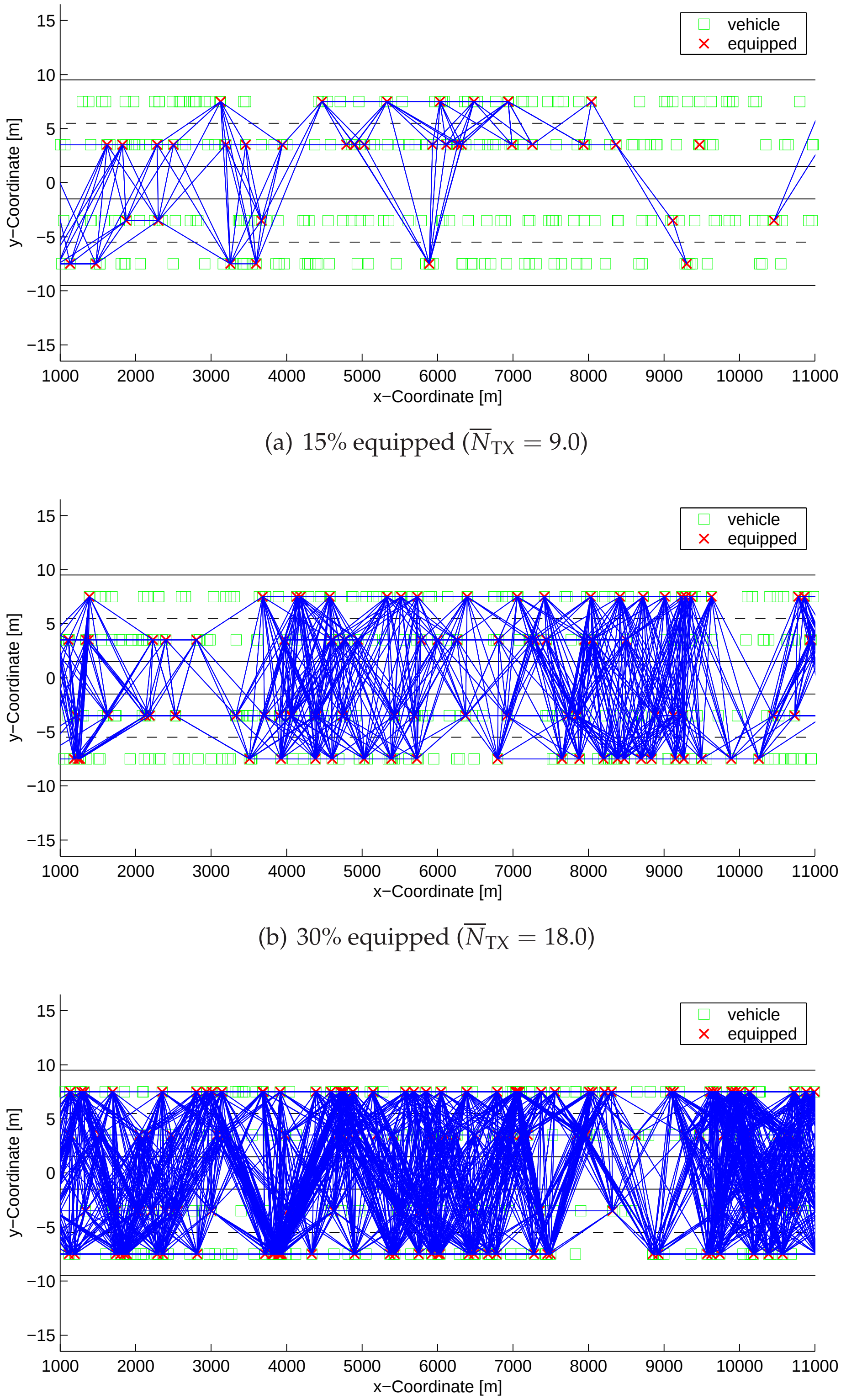


(b) 5% equipped ($\overline{N}_{\mathrm{TX}} = 3.0$)



(c) 10% equipped ($\overline{N}_{\mathrm{TX}} = 6.0$)

Figure 3.6: Sparsely connected VANETs for a 2x2 highway scenario in the simplified model (traffic density $\rho = 7.5\,\mathrm{veh/km/lane}$, transmission range $R = 1\,\mathrm{km}$).



(a) 15% equipped ($\overline{N}_{\mathrm{TX}} = 9.0$)

(b) 30% equipped ($\overline{N}_{\mathrm{TX}} = 18.0$)

(c) 50% equipped ($\overline{N}_{\mathrm{TX}} = 30.0$)

Figure 3.7: Dense VANETs for a 2x2 highway scenario in the simplified model (traffic density $\rho = 7.5$ veh/km/lane, transmission range $R = 1$ km).

These observations are also supported by an alternative analytical model for one-directional highway traffic presented in [WFR04]. Since in this case transport on-board of vehicles on the opposite lane is not feasible, a very limited information propagation for sparse VANETs is observed.

3.6.2 Dense VANETs

In dense VANETs, the expected number $\overline{N}_{\mathrm{TX}}$ of communication partners within transmission range exceeds 10.0, according to the definition in the previous section. Figure 3.7 plots examples for VANETs on a 10 km 2x2 highway segment. If 30% of all vehicles are equipped at an assumed traffic density of 7.5 veh/km/lane, the network is connected over large distances.

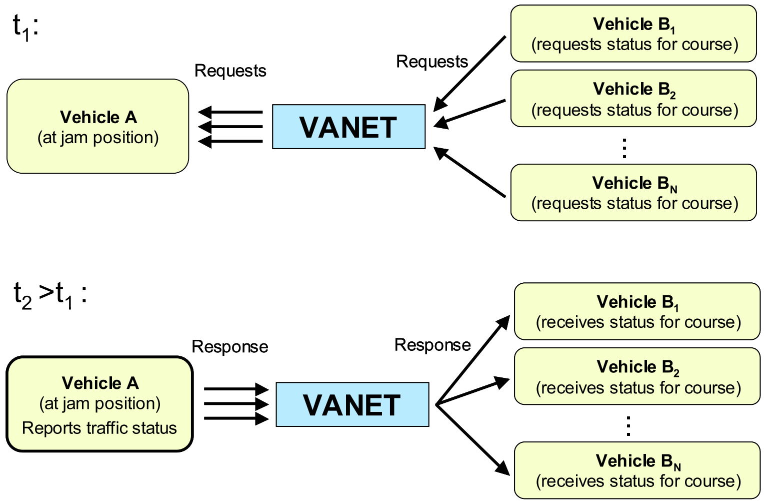
In a dense VANET, information can be forwarded in large distances via the wireless link much faster than it would be forwarded onboard the vehicle. An optimal data dissemination algorithm would therefore use wireless communication to forward the information whenever possible and switch to transport onboard the vehicle only if no suitable communication partner is in range.

3.7 Known Data Dissemination Techniques

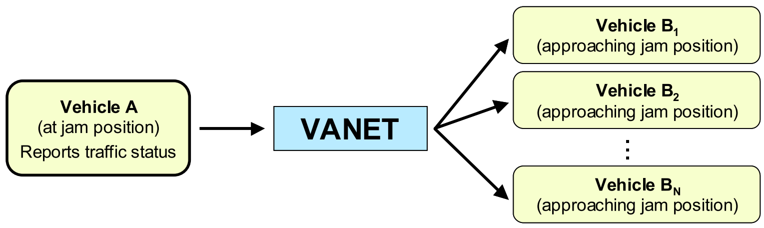
A number of data dissemination schemes targeted at VANETs have been proposed in literature. Following a short introduction to the application of push and pull paradigms to communication in VANETs, this section gives an overview of known data dissemination approaches, their properties and suitability for sparse and dense VANETs.

3.7.1 Communication Paradigms

In a VANET, communication often considers reporting specific events such as an emergency at a specific road position. Event based communication can be organized either according to the pull or the push communication paradigm [TvS02]. The consequences of applying these paradigms to VANETs are evaluated in the following in order to determine which paradigm is more suitable for the majority of VANET applications.



(a) pull-model



(b) push-model

Figure 3.8: Pull and push communication models in a VANET.

3.7.1.1 Pull Communication Model

The pull communication model is the traditional communication model in the Internet: An application sends a request, the request is forwarded to a node at the destination, and the destination node sends a reply including the requested information. In the example in Figure 3.8(a), each vehicle requiring information, e.g. on the traffic status in a specific area, sends a request for this information to a node in the target area. When this request is received, it is processed and individual reply messages are sent back via the VANET.

Pull communication is very efficient if the diversity of information required by individual users is high. Also, it guarantees that information, which no node is interested in, will not be transmitted at all. For most VANET applications however, pull communication has severe limitations. The distance from source to destination has to be traversed twice causing a high delay. In sparse networks, propagating a request to a vehicle ahead is particularly challenging, since in this direction transport on board a vehicle of the opposite lane cannot be applied (as already discussed in Section 3.6.1).

Since a vehicle will only receive requested information, the reply message also needs to be available before the vehicle reaches the target position. Thus, the allowed delay is limited by the time the vehicle needs to drive to the target position and properties of the information itself (time that information is valid). If information is of general interest, as it would be the case for traffic information or hazard warnings, the pull communication model becomes inefficient, since for each interested vehicle a separate request-reply data exchange is performed.

3.7.1.2 Push Communication Model

In contrast, the push communication model is based on the idea that nodes sensing events of interest continuously "push" the information into the network. For example, a vehicle detecting a traffic jam situation would disseminate this information via the VANET. The information would be forwarded (not necessarily unchanged, e.g. it could be forwarded in an aggregated form) to all vehicles in the local area.

For dissemination of information relevant to a large number of vehicles, this communication model is advantageous: The nodes continuously have the most up to date information available, the distance from source to destination is traversed only once. Additionally, for a position ahead the information can be propagated by vehicles on the opposite lane in low penetration situations.

The maximum age of "useful" information is independent of the time the vehicle needs to the target position and only depends on properties of the information itself. For example in case of traffic information, delays up to 20 to 30 minutes are still acceptable. Thus, in many cases where the pull model cannot obtain information on-time, with the push model the vehicle has accurate information. In combination with a store-and-forward approach, useful information can be provided even in cases of very low penetration.

3.7.2 Overview of Known Dissemination Schemes for VANETs

Data dissemination schemes for VANETs that have been proposed in literature can be grouped in the following two categories:

1. using an (adapted) ad hoc routing mechanism to establish a point-to-point connection from one vehicle to another,
2. flooding the local area (limited by the number of hops or by geocast) of the vehicle.

Routing approaches are typically used by applications applying the pull communication model (Sec. 3.7.1.1), since these applications require a route from source to destination. In contrast, push communication (Sec. 3.7.1.2) can best be implemented based on flooding or broadcast schemes.

Routing Approaches — The first category, specialized routing approaches, is investigated by the majority of data dissemination proposals for VANETs. One approach is to adapt routing schemes known from conventional MANETs – e.g. in [KSA02], modifications of Ad hoc On Demand Distance Vector (AODV) [MMe04] routing for vehicular environments are discussed. AODV is an on demand algorithm which builds and maintains routing tables at each node that indicate which neighboring node can forward data packets to a specific destination.

Vehicles require information on their current position for many applications and a positioning system such as GPS will often be available. Therefore, geographical routing [JPS01] is particularly attractive in VANETs.

In beacon based geographic routing protocols, nodes periodically transmit a short packet (the beacon) indicating their position to other vehicles in range. This allows all nodes to build a neighborhood table including position information. The forwarding decision is then based on the position of other vehicles in range, e.g. the node with the highest progress in direction of the destination is chosen (greedy routing). A typical protocol of this kind is Greedy Perimeter Stateless Routing (GPSR).

A disadvantage of all protocols that maintain routing or neighbor tables, such as AODV and GPSR, is that position and connectivity information is outdated very fast in VANET scenarios because of the high mobility. For example in an evaluation including a detailed road traffic model reported in [NBG06], AODV and GPSR were only able to deliver 12-34 % of all data packets. On average 10-20% of the information in the GPSR tables was invalid. For AODV, 70-95 % of the network traffic was needed for maintaining the routing information.

The problem of outdated neighborhood information is avoided by beacon-less routing protocols [FWK+03, HBBW04]. In these protocols, the forwarding decision is not made by the forwarding node but instead by the receiving nodes which contend based on their position. For high mobility, beacon-less routing strongly outperforms other position-based routing mechanisms [Fre04].

Since geographic routing requires information on the location of the destination node, a location service is required in addition to the routing scheme. In most publications on geographic routing in VANETs, this aspect is ignored and the location service is assumed to be perfect. An exception is Carnet [MJK+00], a location service for geographic routing in vehicular networks.

A major limitation of multi-hop routing schemes is that information can only be disseminated within multi-hop range. For sparse networks (e.g. in case of low market penetration), the multi-hop range is very low. In this case, information can only be obtained for a local area of approximately one to two transmission ranges – as already known from Section 3.6. Thus, virtually all publications investigating multi-hop routing protocols in VANETs assume a dense network (usually all vehicles are equipped with the ad hoc communication system), e.g. [TC03, LMFH05, SYYK06, NBG06].

BROADCAST AND FLOODING APPROACHES — The second category of data dissemination schemes for VANETs are broadcast/flooding approaches. For some applications, e.g. collision avoidance, 1-hop broadcast is sufficient: Local broadcast of a position and velocity vector is sufficient to calculate the probability for a collision of vehicles [UTHO05]. For theses safety applications, a low delay is much more important than achieving a large dissemination range since an additional delay of only 200 ms can result in significantly more vehicle collisions, e.g. in vehicle platoons [BTD06]. A possible concept for the dissemination of safety information using local peer groups is presented in [CC05]: Based on geographic position or radio connectivity, vehicles form groups in which communication is organized to achieve low delays (<100 ms) and reliable communication for safety applications.

For comfort applications, a single hop broadcast often is not sufficient and therefore other schemes have to be applied. An example for the flooding technique is [Mic01], where hop limited flooding is used for the dissemination of traffic information. Additionally, a layered data structure allows a forwarding node to reduce the size of a data packet by discarding information. The idea is to exploit the fact that the required accuracy of (traffic) information is distance-dependent. The system proposed in [Bri01, BH02] also uses hop-limited flooding but maintains a set of neighboring nodes and known senders of the message. If no neighbor for forwarding the message is in range, the message is stored until the set of neighbors changes.

The vehicular information broadcasting relay protocol [MKO00] uses a more complex flooding approach: Packets consist of multiple sub-packets that can be individually decoded and contain information on a specific sensor. Received sub-packets are stored in a local receiving buffer. Flooding is not performed on a per packet basis but instead the vehicle periodically combines received sub-packets of relevance, resulting in an increased efficiency of the flooding process. Disseminating information to all vehicles in range is also feasible by epidemic algorithms [EGKM04, VB00].

COMBINED APPROACHES — An approach similar to dissemination schemes for sensor networks are Content-Addressed Storage (CAS) and Mobile-Assist Storage (MAS) [LMZ+06]. In these, meta data is broadcasted and interested vehicles request the full information. While CAS uses a specific type of infrastructure called *Infostation* to hash and store the full information, in MAS the mobile nodes themselves store the information. A routing and a location service are used to forward requested information to a node.

The Mobility-centric Data Dissemination algorithm for Vehicular networks (MDDV) by Wu et al. [WFGH04] uses a digital map (including a metric based on the number of lanes of a road) for routing. A store-and-forward behavior allows vehicles to hold information while no other vehicles are in range. Data is disseminated in two phases: In the *forwarding phase*, the vehicles use the digital map to calculate a suitable trajectory and forward the information to the destination region. In the *propagation phase*, the message is flooded within the destination area. MDDV has a high complexity but can disseminate the information in a larger range than usual routing approaches since the store-and-forward component avoids the need for end-to-end connectivity. A similar procedure – although not primarily targeted at VANETs – is the Delay Tolerant Network Architecture [BHT+03, Fal03] and the data mule concept [SRJB03]. Another opportunistic resource exchange protocol for inter-vehicle networks is presented in [XOW04], where a relevance function is used to estimate the importance of disseminated data. It determines the maximum distance and the maximum age for distributed data values.

Compared to the previously mentioned approaches, the technique proposed in the following chapters is different in various aspects: The transmission and reception of data packets is completely decoupled, no routing is required and the rate at which a node sends data packets is adapted to the local environment. Information for a specific region is abstracted and instead of unchanged forwarding of data packets, the vehicles modify and update data packets.

IV

System Assumptions and Scope of Thesis

The thesis investigates two fundamental issues for data dissemination in VANETs: For sparsely connected VANETs, a critical challenge is to allow data dissemination in a large area, i.e. to achieve a large information range despite low penetration of the ad hoc technology. In dense VANETSs, it is of major importance to avoid congestion on the wireless channel and to provide a fair share of the available resources (transmission rate) to all vehicles. A scheme for controlled sharing of the wireless channel can significantly improve the performance in medium dense VANETs with a penetration of about 5 % and becomes more and more important as penetration increases.

For both aspects, solutions are offered in the following chapters. Their performance is evaluated for a wide range of VANET scenarios in order to determine in which situations they are applicable and what performance gain can be expected. Beforehand, the underlying system assumptions are described after listing the observations that lead to this scope of the thesis.

4.1 Observations

For a successful introduction of the VANET concept, data dissemination schemes need to be able to cope with a low density of equipped vehicles, i.e. market introduction. Summarizing the previous two chapters, the following key observations have been made for VANETs where a low ratio of vehicles is equipped (<10%):

Observation 1: Conventional routing and packet forwarding approaches fail. Due to the short multi-hop range, even an optimal routing scheme is unable to disseminate the information in a large range. (This observation is confirmed and investigated in detail in Chapter 5.)

Observation 2: A combination of information forwarding via the wireless link and transport onboard the vehicle is required.

Observation 3: Communication according to the push model, where vehicles transmit sensed information to potentially affected vehicles without waiting for requests, can provide information more efficiently for most VANET applications.

Although several data dissemination algorithms have been proposed for VANETs, they often do not systematically address these issues and are tested in scenarios with a high density of equipped nodes only.

While the ability to cope with a low density of equipped vehicles is of high importance, a second important aspect is the scalability of the VANET, in particular the question of congestion control for the wireless channel. Due to the broadcast/geocast approach of most VANET applications, conventional schemes known from mobile ad hoc networks cannot be applied.

Observation 4: Most VANET applications are based on broadcast or geocast communication.

Observation 5: There is a lack of suitable congestion control schemes for VANETs.

4.2 *Application Characteristics*

The application characteristics assumed in the thesis are those of a typical VANET comfort application. The data that is disseminated by the application is not critical, i.e. the safety of the driver does not depend on its reception. A varying delay can be tolerated and data is transmitted in a best effort way. The vehicle is interested in information on a relatively large geographical area, for example within a radius of 100 km from the current position. Multiple vehicles can benefit from the data, a point-to-point communication is not required.

Most comfort applications providing travel related information have these characteristics (Section 3.2). In some cases, even safety relevant information is included. For example the VANET based Self-Organizing Traffic Information System (SOTIS) presented in Section 6.1 also includes safety functions such as hazard warning.

This class of comfort applications is attractive since it can provide benefit for the driver even during the phase of market introduction of a VANET technology. Furthermore, since the requirements regarding security and reliability of data dissemination are lower than for safety applications, it allows to gain experience with a large scale deployment of a VANET at a relatively low risk.

4.3 Communication

The techniques for data dissemination proposed in the thesis are implemented above the link and physical layer of an IVC system. As mentioned in Section 2.3, for these two lower layers several suitable proposals, e.g. the IEEE 802.11p draft, exist and are currently in the standardization process.

The system assumptions regarding communication take this development into account. Regarding the complexity, a compromise between scalability of the simulation and sufficient level of detail has to be made. On the one hand, many effects can only be investigated if the VANET scenario includes several thousand vehicles. On the other hand, a level of detail which is too low can invalidate the obtained results.

4.3.1 Wireless Channel

For modeling radio propagation, the large-scale propagation models known from Section 3.4 are used. If not indicated otherwise, log-distance path loss with log-normal shadowing is assumed. However, the influence of the other propagation models on the obtained simulation results is an important aspect that is evaluated as well. Small-scale propagation is neglected in most simulations, since a LOS situation will often be the case and a suitable physical layer can mitigate the influence of frequency selectivity. Nevertheless, in order to illustrate the effect that fast fading has on the results, additional simulations applying a Ricean flat fading model are performed for the identical scenario in selected cases.

4.3.2 Physical Layer and Medium Access

A promising physical/link layer candidate for IVC today is the WLAN-like proposed IEEE 802.11p standard. Therefore, a CSMA based system similar to

IEEE 802.11 will be assumed in all performance evaluations, if not indicated otherwise. However, all proposed mechanisms are independent of the type of medium access control and can be applied in VANETs using other medium access schemes, analogously.

More specifically, the Distributed Coordination Function (DCF) of the IEEE 802.11 MAC protocol [IEE99a] is modeled, including binary exponential backoff (refer to Section 3.5 for more information). Additionally, in order to get an impression what impact a more optimal MAC protocol than IEEE 802.11 would have, some simulations are performed with an ideal MAC, which avoids data packet collisions completely.

Regarding data corruption due to noise and interference, a packet-level error model is applied as provided by the used wireless network simulator. It utilizes a threshold based reception model: A packet is detected if the power at the receiver exceeds or is equal to the carrier-sense threshold (see Section 3.5), a packet can be received successfully if the power is equal to or larger than the receive threshold. For a deterministic radio model such as the used two-ray ground model, the required receive threshold is determined solely by the desired transmission range R and calculated as the power predicted by the propagation model at the distance R. For the carrier sense range, a common assumption is to use a value of approximately twice the transmission range ($2\,R$) [YV05], which is also done here.

Data packet collisions are taken into account. Additionally, the capture effect of the radio channel [Tan88] is incorporated by a capture threshold: If the ongoing reception of a data packet is interfered by the simultaneous transmission of another packet, the ratio of the received power to the interfering power is calculated. If this ratio is equal to or exceeds the capture threshold, it is assumed that the ongoing reception is not corrupted by the interfering packet (capture effect). Otherwise, a collision occurs.

4.4 Mobility Model

It is well known that mobility has a strong influence on the performance of applications and protocols in mobile ad hoc networks [HBWP04]. Therefore, a network model considering the specific mobility patterns in a VANET is of particular importance.

For modeling a city scenario with a rather dense road pattern on a limited area of a few square kilometers, the Random Way-Point (RWP) mobility model is a commonly used approximation [SJ04]. In RWP, a node chooses a random destination from an uniform two-dimensional distribution for the simulation area. Afterwards, it moves with constant speed at a straight line towards the destination. After arrival, it pauses a random time before it chooses a new destination.

Studies have shown that the results obtained for the RWP model can change significantly if a more realistic microscopic road traffic model is used – even for city scenarios [NBG06]. In a highway scenario, the RWP model is not suitable at all. In this case, the mobility is strongly influenced by the pattern of highways, the specific traffic situation and the driver behavior. In order to reflect these influences, a vehicular traffic simulation needs to be integrated into the network simulations.

Based on a map of highways, a Cellular Automaton (CA) microscopic vehicular traffic simulation (see Appendix A) is used in this thesis to calculate the position and speed of each vehicle in a scenario. It considers the specific vehicle and (partially random) driver behavior and models details such as lane changes or mutual influence of vehicles. Note that to take the mutual influence into account, all vehicles – including those without ad hoc communication capability – need to be modeled.

The positions of the vehicles are used within the network simulator to determine the network topology and reception situation at each instant in time. This combination of vehicular traffic and network simulation allows a detailed modeling of the network topology at a moderate computational complexity. By variation of the parameters of the vehicular traffic simulation, a wide range of vehicular scenarios can be evaluated.

V

Constraints of Data Dissemination in Vehicular Ad Hoc Networks

This chapter considers basic limitations for the communication in a VANET. Data dissemination for varying levels of IVC market penetration is investigated. These considerations lead to the important conclusion that multi-hop routing strategies as known from other mobile ad hoc networks are not suitable for sparsely connected VANETs. However, in a subsequent section, it is shown that information dissemination is feasible, if a forwarding scheme is assumed which additionally makes use of the transport onboad the vehicle. For this class of forwarding schemes, an approximation of the speed of information dissemination is derived. It proves that distributing information in a large range is possible with reasonable delay even in case of low market penetration.

5.1 Communication Time and Multi-Hop Range

Two important properties in a VANET are the communication time between two individual vehicles and the feasible multi-hop range in the network. In order to obtain an approximation for these two characteristics, a simple analytical model of the VANET is used.

5.1.1 Simplified Analytical Topology Model

The analytical model for the topology of the VANET considers the movement of vehicles in a mesoscopic traffic model (see Appendix A):

- The distance between two successive vehicles (headway) is characterized as a random variable which follows an exponential distribution.

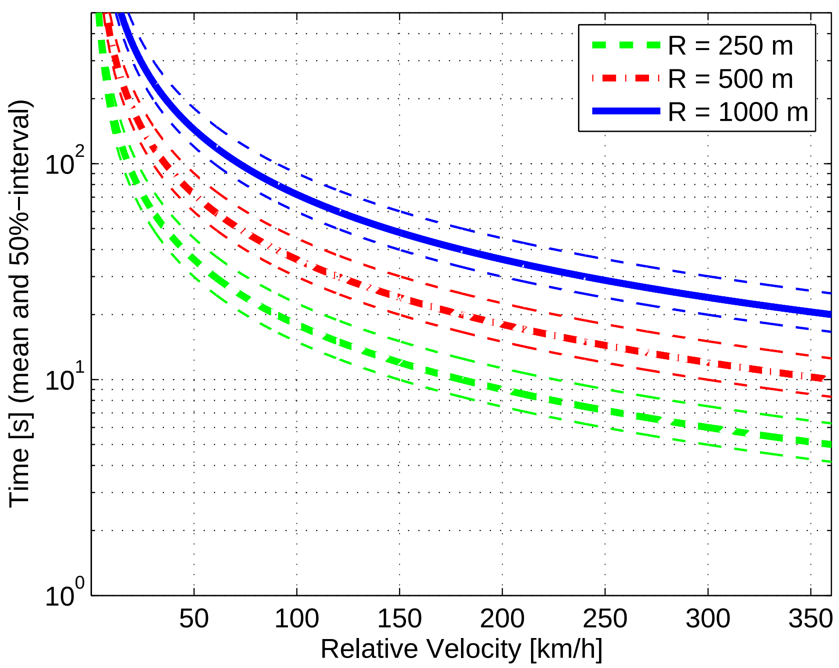


Figure 5.1: Communication time depending on relative velocity and transmission range R (analytical model).

- Transmission range R of the ad hoc air interface is constant and identical for all vehicles.
- All vehicles have the same velocity (but may have different directions).

5.1.2 Communication Time

The communication time is the time during which two vehicles can communicate in a single encounter. Figure 5.1 shows the resulting communication time in seconds if the relative velocity is varied. The thin dashed lines indicate the 50%-interval if – instead of being identical – statistically independent Gaussian distributed random velocities are assumed as suggested in [RMJ03]. Due to the assumed independence, the resulting relative velocity is also a Gaussian variable. Here, a standard deviation of $\sigma_V = 0.3\mu_V$ is used. The figure illustrates that typical relative velocities for oncoming traffic on highways result in a communication time in the range of 4 s to 40 s, depending on the assumed transmission range R.

For the Gaussian velocity model, the Cumulative Distribution Function (CDF) $F_{\mathrm{Tcom}}(t)$ of the communication time is of high interest. It indicates the probability that the communication time T_{com} is smaller than or equal to a specific value t. For a constant assumed communication range R, the communication time T_{com} is a function of the relative velocity represented by the random variable V_{rel}.

$$T_{\mathrm{com}} = \frac{2R}{V_{\mathrm{rel}}} \tag{5-1}$$

Since (5-1) is a bijective function, the resulting Probability Density Function (PDF) and CDF of T_{com} can be calculated based on the PDF of the relative velocity [Pap91]. For a Gaussian distribution of V_{rel}, the resulting PDF and CDF are given by (5-2) [RMJ03].

$$\begin{aligned} f_{\mathrm{Tcom}}(t) &= \frac{2R}{\sqrt{2\pi}\sigma_{\mathrm{V}} t^2} \cdot \exp\left(- \frac{\left(\frac{2R}{t} - \mu_{\mathrm{V}}\right)^2}{2\sigma_{\mathrm{V}}^2} \right) \\ F_{\mathrm{Tcom}}(t) &= P(T_{\mathrm{com}} \leq t) = \int_{-\infty}^{t} f_{\mathrm{Tcom}}(\tau) \ \mathrm{d}\tau \end{aligned} \tag{5-2}$$

Figure 5.2 plots the CDF for various assumed mean relative velocities μ_{V} (standard deviation of $\sigma_{\mathrm{V}} = 0.3\mu_{\mathrm{V}}$, as in the previous figure). For high relative velocities of μ_{V} in the range 150–350 km/h (commonly observed on highways for vehicles driving in opposite directions), the resulting communication time is in the range of ≈10–20 s. Thus, even with a moderate transmission range of 500 m, the communication time is long enough to allow the exchange of a significant amount of data. E.g., using a 1 Mbit/s IVC standard, approximately 1–2 MB of data could be exchanged during a single encounter.

5.1.3 Feasible Multi-Hop Range

Besides statistics for the communication time between *two* arbitrary vehicles, the range in which multi-hop communication is feasible is an important characteristic of the vehicular network. It is the range in which a conventional ad hoc routing protocol could possibly disseminate information. Obviously, this parameter depends mainly on the density of vehicles equipped with the communication device (i.e. market penetration and vehicular traffic density) and the transmission range of the air interface.

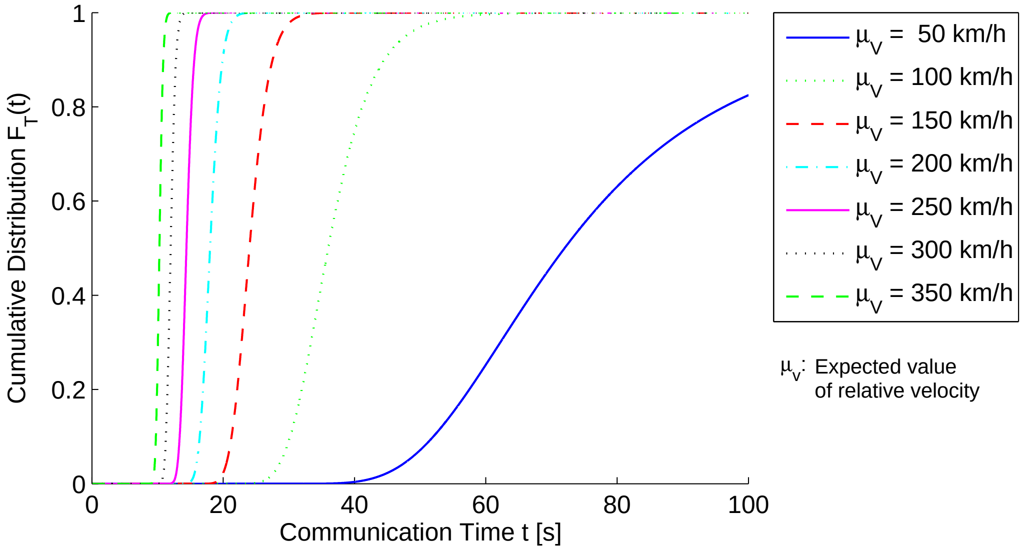


Figure 5.2: Cumulative distribution function of communication time for various relative velocities (Gaussian distributed, analytical model) and a transmission range $R = 500\,\text{m}$.

To obtain an analytic approximation of the average multi-hop range, results from the theory of coverage processes [Hal88] are applied to the considered multi-hop scenario in [Ebn05a]: On an individual street, sections in which vehicles can communicate using multi-hop communications ('clumps' in the theory of coverage processes) alternate with sections not covered by any wireless air interface ('spacings'). For this spatial alternating renewal process, clumps are formed by a superposition of individual segments of length R, where R is the transmission range of the air interface. The expected value of the clump length C corresponds to the average range $\overline{R}_{\text{mhop}}$ in which multi-hop communication is possible.
For a fixed length R, the expected clump length is given by [Hal88, Ebn05a]:

$$\overline{R}_{\text{mhop}} = E\{C\} = \frac{e^{R\kappa} - 1}{\kappa}. \tag{5-3}$$

For calculating the intensity κ, the following simplifications are made:

1. A constant traffic flow volume q per lane is assumed. All vehicles travel with a fixed velocity v.

2. The headway is exponentially distributed.

3. Communication occurs instantly and without any errors or delays.

In this case, the parameter κ is

$$\kappa = N_{\mathrm{L}}\gamma\frac{q}{v} = N_{\mathrm{L}}\gamma\rho \tag{5-4}$$

where γ (with $\gamma \in [0, 1]$) denotes the assumed penetration of the ad hoc system, N_{L} the number of lanes (sum over both directions) and ρ is the traffic density (vehicles per kilometer per lane).

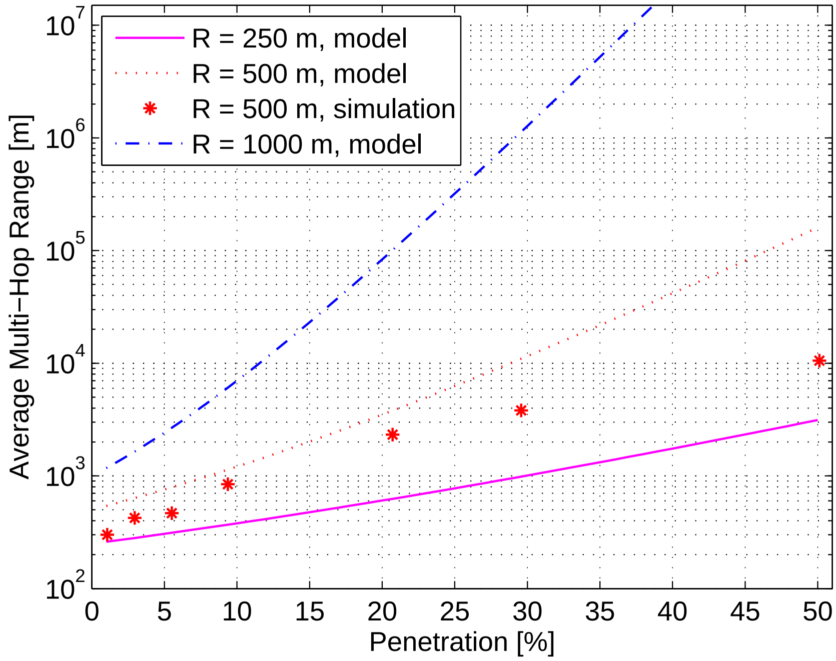


Figure 5.3: Expected multi-hop range.

Figure 5.3 shows the expected multi-hop range for a highway traffic scenario with a relatively low traffic density of 7.8 veh/km/lane when the penetration γ is varied. For comparison, the results from a detailed simulative performance evaluation presented in [Kho05] are plotted. This simulative evaluation considers a realistic position-based routing protocol (Beacon-Less Routing [HBBW04]), a CSMA based medium access protocol and physical layer effects such as packet corruption and limited data rate. Therefore, the achieved multi-hop range in the simulations is significantly lower than the optimum value calculated according to Equation 5-3.

The main conclusion drawn from Figure 5.3 is that by classical multi-hop communication, the information can be distributed in only a very limited range if the market penetration is low. For example, at a market penetration of 5% and a transmission range of the air interface of 1000 m, the average information range is about 2 km – even if optimal routing and communication are assumed. Obviously, the classical routing based schemes used in regular MANETs are not suitable for VANETs in low penetration situations due to the resulting low information ranges.

5.2 Speed of Information Dissemination

The remainder of this chapter investigates data dissemination techniques for vehicular ad hoc networks, in particular how far and with which velocity the information can be distributed. It is distinguished between two ranges [WER05a, Ebn05a]: The *multi-hop range* R_{mhop} is the range in which information can be distributed by multiple hops via the wireless link at a specific point in time. The *information range* R_{info} is the range for which the vehicle can acquire information. Depending on the technique used for information dissemination, the information range can exceed the multi-hop range by far.

In the following, an approximation for the speed of information dissemination for an *optimal* data dissemination scheme is derived. Therefore, the simple analytical model from Section 5.1.1 is extended and the following additional properties are assumed:

- Ideal communication (unlimited bandwidth, error-free, no packet collisions)
- Constant per-hop delay $\overline{\tau}_{\text{hop}}$ (time until data received at a node is processed and forwarded)
- Optimal multi-hop forwarding: Information is always forwarded by the vehicle achieving maximum progress in the desired direction of information dissemination.
- Stationary network during the multi-hop procedure: For simplification, it is assumed that the topology is stable during the multi-hop forwarding process (i.e. forwarding time is short compared to the time scale for significant topology changes).

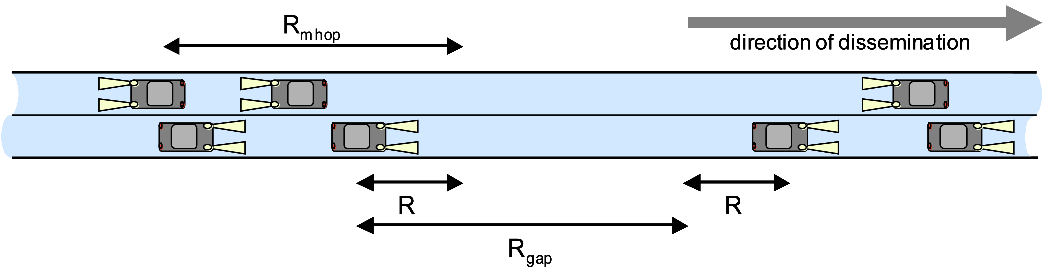


Figure 5.4: Ranges for multi-hop forwarding and forwarding onboard the vehicle for an example scenario.

In such a scenario, the expected multi-hop range $\overline{R}_{\text{mhop}}$ as illustrated in Figure 5.4 is already known from Equation 5-3. For optimum multi-hop forwarding, the expected value $\overline{d}_{\text{hop}}$ of the per-hop progress in direction of dissemination is derived in [Ebn05a] based on the exponentially distributed headway.

$$\overline{d}_{\text{hop}} = \frac{\kappa R - 1 + e^{-\kappa R}}{\kappa \left(1 - e^{-\kappa R}\right)} \tag{5-5}$$

The parameter κ is known from Equation 5-4 and the expected number of hops in a multi-hop part is approximated by

$$\overline{n}_{\text{mhop}} \approx \frac{\overline{R}_{\text{mhop}} - R}{\overline{d}_{\text{hop}}} + 0.5 \tag{5-6}$$

In this case, the expected time for forwarding in a multi-hop part can be expressed by

$$\overline{T}_{\text{mhop}} = \overline{n}_{\text{mhop}} \overline{\tau}_{\text{hop}} \tag{5-7}$$

Regarding the total achieved progress in the direction of information dissemination, three different situations need to be distinguished:

1. The last vehicle within R_{mhop} drives in the direction of information dissemination (Figure 5.4).

2. Last vehicle does not drive in direction of information dissemination, but within R_{mhop} a vehicle driving in this direction exists (Figure 5.5).

3. Within R_{mhop}, no vehicle drives in direction of information dissemination.

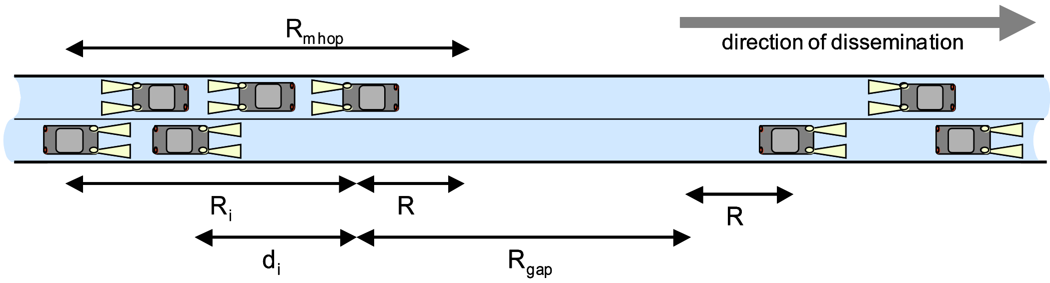


Figure 5.5: Distance d_i to last vehicle in a multi-hop part driving in the direction of information dissemination.

For the first case, the expected value of the total progress due to multi-hop forwarding is $\overline{R}_{\text{mhop}} - R$, as illustrated in Figure 5.4. This is the best case and for simplicity it is assumed that it occurs with a probability of 0.5, which is a valid assumption if the number of hops in the chain is large.

In case the last vehicle drives in the opposite direction, the progress due to multi-hop forwarding needs to be considered up to the last vehicle in direction of dissemination. (Only a vehicle driving in the direction of dissemination can later forward the information onboard in the proper direction.) Such a vehicle exists in range $R_{\text{i}} = R_{\text{mhop}} - R$ with the probability

$$P_{\text{i}} = 1 - e^{-\kappa_{\text{i}} R_{\text{i}}} \tag{5-8}$$

since for each direction an exponential distribution of the distance X_{i} between successive vehicles with expected value $\frac{1}{\kappa_{\text{i}}} = \frac{2}{\kappa}$ is assumed. Thus, in total the second situation occurs with a probability of $0.5P_{\text{i}}$.

Applying the condition $X_{\text{i}} < R_{\text{i}}$ leads to the PDF $f_{X_{\text{i}}|X_{\text{i}}<R_{\text{i}}}(x) = e^{-\kappa_{\text{i}} x}(1 - e^{-\kappa_{\text{i}} R_{\text{i}}})^{-1}$ for $x \in [0, R_{\text{i}}]$. With this PDF, the expectation value $\overline{d}_{\text{i}}$ of the distance to the last vehicle in direction of dissemination can now be calculated:

$$\overline{d}_{\text{i}} = E\{X_{\text{i}}|X_{\text{i}} < R_{\text{i}}\} = \frac{1 - e^{-\kappa_{\text{i}} R_{\text{i}}}\left(\kappa_{\text{i}} R_{\text{i}} + 1\right)}{\kappa_{\text{i}}\left(1 - e^{-\kappa_{\text{i}} R_{\text{i}}}\right)} \tag{5-9}$$

The resulting progress in direction of information dissemination for this situation is $R_{\text{i}} - d_{\text{i}}$.

The third situation (no vehicle in direction of dissemination) occurs with the probability $0.5(1 - P_{\text{i}})$ and achieves no progress due to multi-hop forwarding. The vehicle initially informing the multi-hop group will also transport it onboard after passing the R_{mhop}, i.e. the multi-hop part has no positive effect for (long-term) information dissemination and the information is disseminated with the vehicle velocity $\overline{v}$.

Therefore, the velocity of information dissemination v_{mhop} in the multi-hop case exceeds $\overline{v}$ only in the first two situations. Its expectation value $\overline{v}_{\text{mhop}}$ is

$$\overline{v}_{\text{mhop}} \approx \frac{0.5R_{\text{i}} + 0.5P_{\text{i}}\left(R_{\text{i}} - \overline{d}_{\text{i}}\right)}{\overline{T}_{\text{mhop}}} + 0.5(1 - P_{\text{i}})\overline{v} \tag{5-10}$$

Analogously, the time and velocity for the transport onboard the vehicle can be approximated. The expected value for the distance $\overline{R}_{\text{gap}} + R$ to the next vehicle on the opposite lane is equal to $R + 2/\kappa$.

$$E\{R_{\text{gap}} + R | R_{\text{gap}} > 0\} = R + \frac{1}{\kappa_{\text{i}}} \tag{5-11}$$

The time to close the gap is determined by the relative velocity $2\overline{v}$.

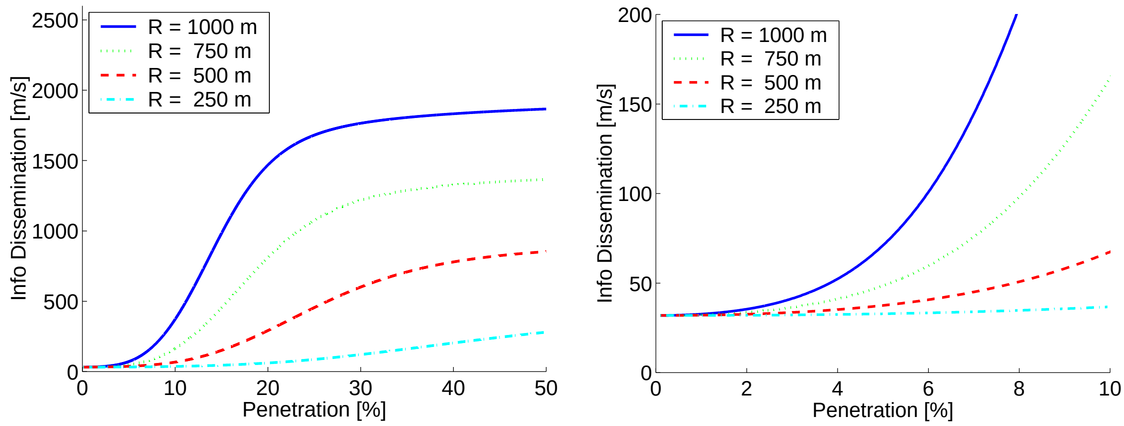
$$\overline{T}_{\text{gap}} \approx \frac{1}{2\kappa_{\text{i}}\overline{v}} \tag{5-12}$$

The total velocity of information dissemination $\overline{v}_{\text{info}}$ is therefore approximated by a combination of $\overline{v}_{\text{mhop}}$ in the multi-hop case and vehicle velocity $\overline{v}$ during the transport onboard.

$$\overline{v}_{\text{info}} \approx \frac{\overline{T}_{\text{mhop}}}{\overline{T}_{\text{mhop}} + \overline{T}_{\text{gap}}}\overline{v}_{\text{mhop}} + \frac{\overline{T}_{\text{gap}}}{\overline{T}_{\text{mhop}} + \overline{T}_{\text{gap}}}\overline{v} \tag{5-13}$$

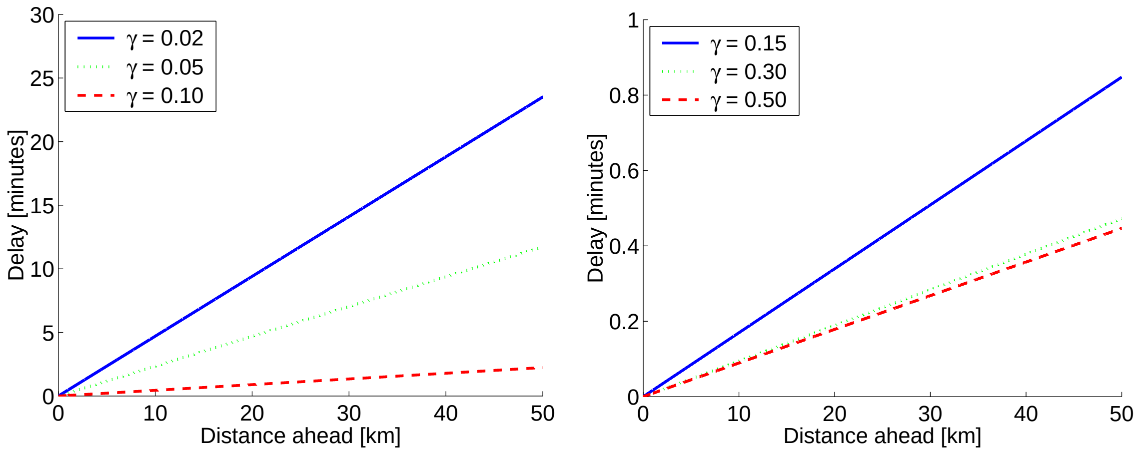
Figure 5.6 plots this approximation for a traffic scenario with a traffic density of 7.5 veh/km/lane. It can be observed that for a low market penetration γ the forwarding speed is determined by the vehicle's velocity whereas for a high penetration it approaches $R/\overline{\tau}_{hop}$. Influence of multi-hop forwarding becomes visible at a market penetration of about 7-10% for a transmission range of 500 m.

The resulting delay for information originated at a specific distance is plotted in Figure 5.7, where a constant transmission range of 1000 m is assumed. The results are confirmed by simulative evaluation in the next chapter and also in good accordance with simulation results reported in [Ebn05a].



(a) market penetration between 0 and 50%   (b) magnification: low market penetration

Figure 5.6: Estimated velocity of data dissemination ($\rho = 7.5\,\text{veh/km/lane}$, $\overline{v} = 32\,\text{m/s}$). Assumes a forwarding delay of $\overline{\tau}_{hop} = 500\,\text{ms}$ per hop.



(a) sparsely connected   (b) dense

Figure 5.7: Estimated delay for data dissemination (optimal communication assumed, $\rho = 7.5\,\text{veh/km/lane}$, $R = 1000\,\text{m}$, $\overline{v} = 32\,\text{m/s}$, $\overline{\tau}_{hop} = 500\,\text{ms}$).

VI

Segment-Oriented Data Abstraction and Dissemination (SODAD)

The previous chapter has demonstrated the need for simple, scalable network procedures for data dissemination in VANETs, which can, in particular, be applied in sparsely connected networks. Therefore, Segment-Oriented Data Abstraction and Dissemination (SODAD), a method for data dissemination for comfort applications, is proposed in this chapter. SODAD is based on the observations that most likely communication will occur in a broadcast/geocast manner and that vehicles need to transport information onboard in order to close communication gaps in fragmented networks.

The main idea is to divide all streets into segments of a specific length, e.g. 100–500 m, and let each vehicle sense data values (e.g. average velocity or temperature) for all segments which it traverses. The segmentation allows to broadcast information in a very efficient way – a single data packet can contain information on more than 50 km of a road. By continuously updating the segment information for the local area with information received via the VANET or sensed by the vehicle itself, a dynamic situation analysis is obtained. Thus, SODAD can be used to create a scalable decentralized information system that provides data in an information range multiple orders of magnitude larger than the transmission range of the air interface even if only 1-3 % of all vehicles are equipped with an IVC system.

For motivation, the first part of this chapter presents an example for a typical VANET application: a Self-Organized Traffic Information System (SOTIS), which offers very detailed traffic information for the local area of a vehicle. SOTIS is a representative comfort application where the SODAD mechanism can be applied. It is used to illustrate the properties of SODAD in the following, however, the SODAD technique can be used for most other comfort applications as well.

In the second part of this chapter, the basic SODAD scheme is introduced and evaluated by network simulations. The influence of the following network parameters is investigated:

- road traffic density,
- market penetration/ratio of equipped vehicles,
- vehicular traffic model,
- radio channel model and
- medium access control protocol.

The last part of the chapter extends the basic SODAD scheme by a heuristic adaptation of the inter-transmission interval. This extension drastically reduces the required data rate and increases the performance in high density situations.

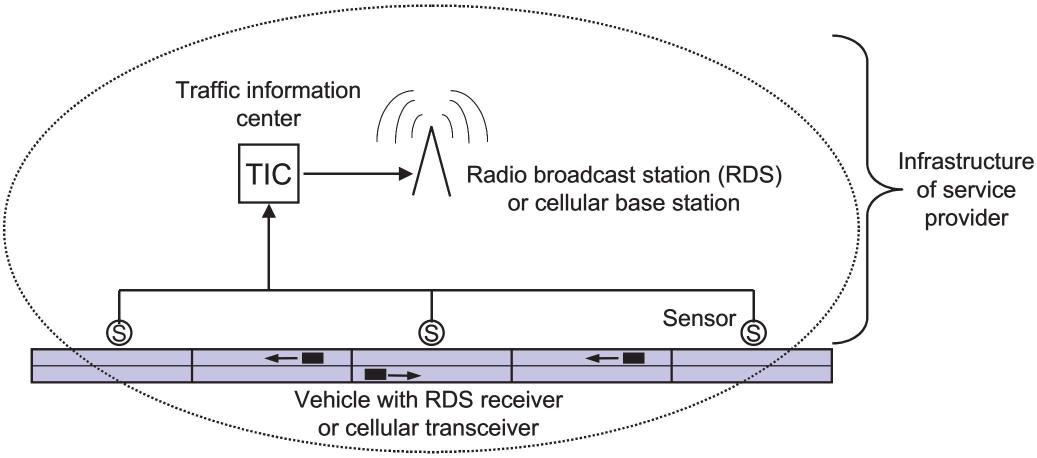
6.1 Example Application: Self-Organizing Traffic Information System

Up-to-date traffic and hazard information for the local area is of high interest for any driver. A Self-Organizing Traffic Information System (SOTIS) [WER$^+$03b, EWER03] based on IVC can provide this information with high accuracy and low delay. This section introduces the SOTIS example, which will be used for illustrating the SODAD method afterwards.

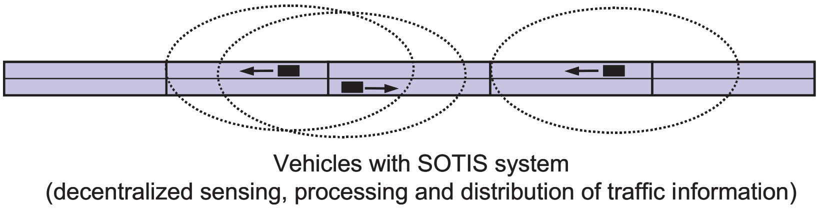
Conventional Traffic Information Systems (TIS) are organized in a centralistic way as illustrated in Figure 6.1(a): Sensor-based traffic monitoring systems deployed directly at the roadside collect information about the current traffic conditions. This data is transferred to a central Traffic Information Center (TIC), where the current road situation is analyzed. The result of this situation analysis is packed into messages for the Traffic Message Channel (TMC), forwarded to the FM radio broadcast station and transmitted via Radio Data System (RDS) to the driver. Alternatively, the traffic messages can be transferred on demand via cellular mobile phone network, e.g. GPRS.

A centralized service for traffic information has several technical drawbacks:

- A large number of sensors needs to be deployed since the service is limited to streets where sensors are integrated. Thus, a large investment for the communication infrastructure (sensors, central unit, wired and wireless connections) is necessary.



(a) Conventional centralized traffic information system.



(b) Decentralized self-organizing traffic information system.

Figure 6.1: Comparison of conventional traffic information systems with a decentralized SOTIS based on VANET communication.

- The recorded traffic density data is transmitted for traffic analysis to a central unit (TIC). This procedure causes a relatively high delay (typically 20-50 minutes), before the result is broadcasted to the drivers.

- Since a central unit covers a relatively large area and due to the limited bandwidth for transmitting the traffic messages, only major events are transmitted. For example, in case of TMC, the data rate is limited to $\approx$ 80 bits/s. A constantly updated and detailed information for the local area is not available.

- Service charges can apply for the traffic information service (content provider) as well as for the cellular distribution of traffic information (network provider).

For these reasons, an alternative and completely different approach for monitoring the traffic situation and distributing the traffic messages to vehicle drivers is proposed. A decentralized self-organizing traffic information system is established by combining a digital map, a positioning system (e.g. GPS) and wireless ad hoc communication among the vehicles. Since the first two components are already available in modern vehicles equipped with navigation systems, the only additional requirement is a wireless interface for IVC. In this decentralized Self-Organizing Traffic Information System (SOTIS), vehicles inform each other of the local traffic situation by IVC as illustrated in Figure 6.1(b). The traffic situation analysis is performed locally in each individual car. No communication/sensor infrastructure is required. For a global route optimization, the SOTIS information for the local area (e.g. for a radius 50–100 km) can additionally be combined with traffic information provided by roadside access points or conventional centralized systems.

For SOTIS, the objective is to acquire state information for all road segments within the local area. The state of a road segment is described by an average velocity value and a flag indicating if an emergency occurred. Additionally, a time stamp is included that specifies when this information was measured. The information on the traffic state can, e.g., be used in the navigation system of the vehicle to calculate a dynamic route update and inform the driver of hazardous situations ahead. By applying SODAD, this information is available even if only a low number of vehicles ($\approx 1 - 3\,\%$) is equipped with IVC.

6.2 Description of SODAD Approach

The SODAD scheme consists of two parts: the acquisition and the dissemination of data. While driving, vehicles sense data such as the current velocity, height or slippery coefficient and store the information on board. In order to reduce the data volume to be disseminated, an abstract information value is calculated based on multiple sensed data values. Whenever two vehicles are within mutual transmission range, their local view is updated with the information of the other car, respectively.

6.2.1 Map Based Data Abstraction

Data distributed in a vehicular information system typically has the following properties:

- It has a spatial component since it describes the situation at a specific location.

- The relevance for a receiver decreases with increasing distance to the location where the data was originally generated. For example, the interest of a driver in price information of a gas station nearby is higher than for a gas station 100 km away. Similarly, in SOTIS traffic information for roads near the location of the vehicle is most important.
- Analogously, delay and accuracy constraints become more relaxed with increasing distance.

These properties are exploited in SODAD: It is assumed that each vehicle is equipped with a digital map. The map is divided into segments of a known length, which can vary based on the type of object (e.g. road) that is considered.

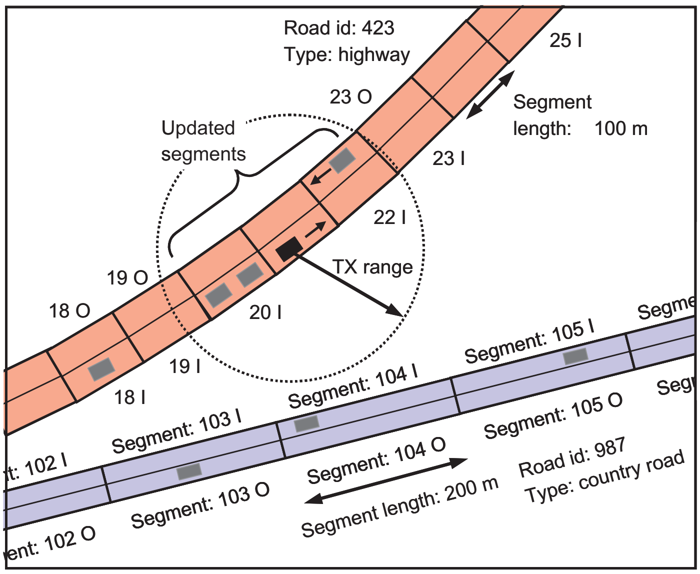


Figure 6.2: Example for map based data abstraction by segmentation of the roads in the local area.

Figure 6.2 shows an example where a vehicle driving on a highway chooses the road segment length automatically and adaptively: A segment length of 100 m is chosen for the highway which the car is driving on and a larger segment length of 200 m is selected for the country road.

The optimal segment size depends on application and road type: Decreasing the segment size increases the level of detail of available information but also leads to a

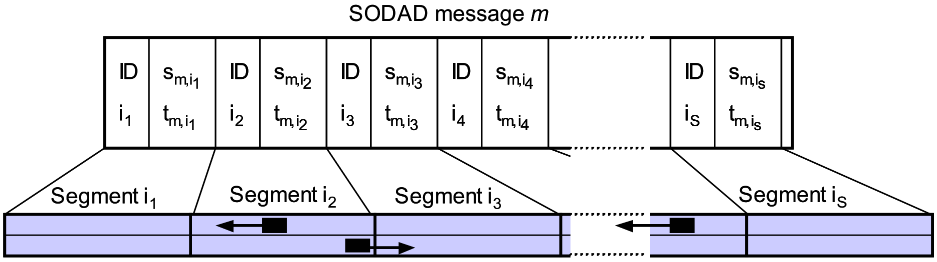


Figure 6.3: SODAD message for a part of the road.

higher data rate. Due to the digital map and a standardized selection of the segment size, each segment can be identified by an unique identifier (segment ID), e.g. the combination of road ID, segment number and direction.

Each node generates information for all segments in transmission range. This is done either by sensing the information itself or by receiving information observed by other vehicles. Depending on the type of application, a node can also be a roadside unit, e.g. gas station, injecting data into the network. In the data abstraction process, a data aggregation function is applied: If N information values $d_1, d_2, \ldots, d_N$ have been received/sensed at node n for a segment i, the new information value $s_{n,i}$ is calculated by applying the aggregation function $a(\cdot)$:

$$s_{n,i} = a(d_1, d_2, \ldots, d_N) \tag{6-1}$$

The nature of the aggregation function depends on the application, for example the mean of $d_1, d_2, \ldots, d_N$ can be calculated or the maximum can be chosen. Additionally, a time-stamp $t_{n,i}$ is set to the current global time (obtained via GPS). The pair $(s_{n,i}, t_{n,i})$ completely describes the information available for a segment at a node.

This process ensures the scalability of the information system: Only one pair $(s_{n,i}, t_{n,i})$ per segment is distributed, independently of the number of values that were sensed by the individual vehicles. Furthermore, by using an adaptive broadcast scheme (as discussed in Section 6.4 and Chapter 8), vehicles can adapt their transmission behavior based on segment information broadcasted by other nodes. Overload conditions are avoided and the data rate for an application is the result of segment length, area to be covered, and the frequency with which the per segment information changes. A higher number of equipped vehicles improves the accuracy and decreases the delay with which data is distributed, as outlined in the following sections.

6.2.2 Data Dissemination

The second part of SODAD is the dissemination of the per-segment information by using the wireless link. The main objective is that data dissemination over large distances is achieved, even in cases of low penetration or low density of vehicles. Therefore, the wireless communication is based on two principles:

1. **Local Broadcast:** All data packets are transmitted in form of local (1-hop) broadcasts. Nodes are never directly addressed and no routing of data packets in the traditional sense (i.e. on the network layer) is performed.

2. **Application Layer Store-and-Forward:** Since all data is sent in form of one-hop broadcasts, the application is responsible for forwarding the per-segment information. It recurrently sends broadcast packets with its current information on all relevant segments in the local area (Figure 6.3).

   Information received at a node is always analyzed and compared with the previously available information. Only if the received information is still relevant and more accurate than the previously known information, it will be stored on-board the vehicle. If message m containing information for S distinct segments with IDs $i_1, \ldots, i_S$ is received at node n, the pairs $(s_{n,k}, t_{n,k})$ are updated by applying a data compression function $c(\cdot)$. It combines the received data values with the information previously stored onboard the vehicle based on the time stamps.

   $$(s_{n,k}, t_{n,k}) = c\left(s_{n,k}, s_{m,k}, t_{n,k}, t_{m,k}\right), \quad k = i_1, \ldots, i_S \qquad (6\text{-}2)$$

   Here, $s_{m,k}$ and $s_{n,k}$ are the information values for segment with ID k in the message and at the node, respectively, and $t_{m,k}$, $t_{n,k}$ are the corresponding time stamps.

Example: A simple variant of the compression function $c(\cdot)$, which is assumed for simulative performance evaluation in the following, simply updates the available

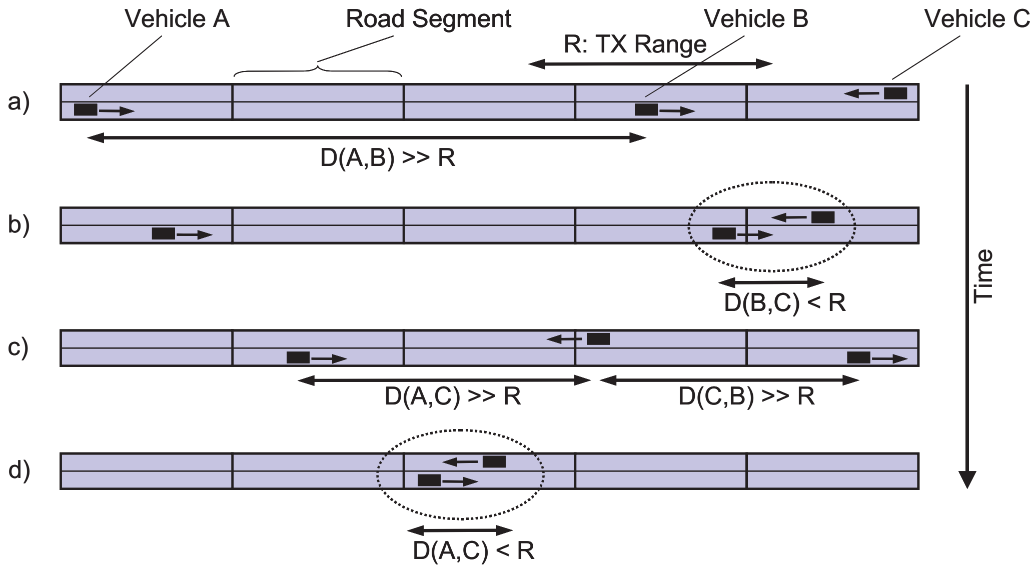


Figure 6.4: Information dissemination in cases of low penetration.

information with the received value if its time stamp is newer:

$$
\begin{aligned}
s_{n,k} &\leftarrow \begin{cases} s_{m,k}, & \text{if } t_{m,k} > t_{n,k}; \\ s_{n,k}, & \text{otherwise} \end{cases} \\
t_{n,k} &\leftarrow \max(t_{m,k}, t_{n,k}); \quad k = i_1, \ldots, i_S
\end{aligned} \tag{6-3}
$$

The effect of this communication paradigm is shown in Figure 6.4, which illustrates the communication in situations with a low density of equipped cars: In 6.4 a), Vehicle A and Vehicle B are driving in the same direction. Vehicle B senses the conditions ahead of Vehicle A but since the distance $D(A, B)$ between the two vehicles is much larger than the transmission range R, they cannot communicate directly. Later, in 6.4 b), Vehicle C on the opposite lane is in transmission range of Vehicle B. It receives and stores the broadcasted per-segment data. In 6.4 c), the vehicles travel for a while without any communication partner in range. Finally, in 6.4 d), Vehicle A can receive the information from Vehicle B although both vehicles were never in (single- or multi-hop!) communication range.

6.3 Simulative Evaluation

In order to evaluate the performance of SODAD, a model has been implemented within the discrete event network simulator[1] *ns-2*. The simulation and system parameters as well as modifications and extensions of the simulator are outlined in the following.

6.3.1 Simulation Model and Parameters

The system-level simulation consists of a vehicle mobility model and a model of the communication system. The stochastic vehicular traffic model is already known from Section 4.4. It uses a microscopic traffic simulation (cellular automaton model, details in Appendix A.4). For an initial performance evaluation, a basic scenario (referred to as *Scenario A* in the following) is defined which uses a deterministic radio propagation model and a traffic simulation without Velocity-Dependent Randomization (VDR). It simulates a typical highway situation with two lanes per direction. The focus is on a highway scenario because, in general, it is more demanding than a city scenario due to the high velocities. Furthermore, information dissemination in two-dimensional arterial networks is easier to achieve than in this one-dimensional highway case [YR05].
Table 6.1 lists the parameters used for road traffic simulation. Arrival times are assumed to be Poisson distributed, initial time gaps between adjacent vehicles are therefore chosen from an exponential distribution. More complex simulation scenarios including VDR and stochastic radio propagation models are presented in the second part of this chapter.

6.3.2 Communication Model and Parameters

The link layer applied in the performance evaluation is a standard IEEE 802.11 system [ANS99] with a data rate of 1 Mbit/s. It has to be pointed out that the proposed methods do not require a specific wireless transmission technology. For the basic scenario (Scenario A), the deterministic two-way ground propagation model (see Section 3.4) is used.

[1] Version 2.29, available at `http://www.isi.edu/nsnam/ns/`

Table 6.1: Parameters used in the traffic simulation (Scenario A).

Parameter	**Value**
Total Road Length	250 km
Number of Lanes	2 per direction
Deceleration Probability	0.4 (no VDR)
Constitution of Traffic	15 % slow, 85 % regular vehicles
Desired Velocity	108 km/h (slow), 142 km/h (regular)
Traffic Density	7.5 veh/km/lane, 10 veh/km/lane, 15 veh/km/lane
Mean Velocity	106.4 km/h, 101.3 km/h, 95.6 km/h

Table 6.2: Communication parameters for basic scenario (Scenario A). Parameter values are based on the default parameters of the ns-2 IEEE 802.11 model.

Parameter	**Value**
Radio Propagation Model	two-way ground (deterministic)
MAC Model	IEEE 802.11 (ad hoc mode)
PHY Data Rate	1 Mbit/s
Transmit Frequency	2.472 GHz
Transmit Power	15 dBm
Transmit Range R	1000 m (if not noted otherwise)
Receive Threshold	adapted to achieve transmit range R
Carrier Sense Threshold	adapted to achieve a range of $2R$
Capture Threshold	10.0
Heights h_t, h_r of Transmitter/Receiver	1.5 m

Table 6.2 summarizes the communication parameters for this scenario. All packets are transmitted as broadcast. The receive threshold is adapted in order to achieve a communication range of 1000 m, since this is the expected range of air interfaces developed for IVC, e.g. DSRC [ZR03] or UTRA TDD Ad Hoc [ERW$^+$03]. Omnidirectional antennas at a height of 1.5 m are assumed.

6.3.3 SODAD Parameters

A resolution of 500 meters is usually sufficient for traffic related information. For simplicity, a constant segment size of 500 m is used. Each equipped vehicle transmits two broadcast packets per second. Of these packets, 66 % include traffic information for the road that the vehicle travels on, the remaining packets are reserved for transmitting information for other roads. For evaluating the system performance, the information stored in the knowledge base of each car is analyzed every 500 ms of simulated time and the respective delay with which each information element has been received is calculated.

For each of the three simulated traffic densities, the performance is evaluated if 2 %, 5 % and 10 % of all vehicles are equipped.

6.3.4 Results

The main objective of the simulations is to evaluate if the SODAD technology can provide traffic information with a reasonable delay. In Figure 6.5(b), results from a typical scenario with a traffic density of 10 veh/km/lane are shown. The average delay of information about a specific road segment increases linearly with its distance from the current position, as predicted in Section 3.7. For a situation where 10 % of all vehicles are equipped with SODAD technology, the information delay is small (≈ 3.5 s/km). Even if only 2 % of all vehicles are equipped, information is successfully distributed. In this case, the delay increases to ≈ 31.4 s/km, which is still acceptable for comfort applications such as SOTIS, given the relatively large time scale on which traffic conditions usually change. A state-of-the-art conventional traffic information system with an average delay of 20 minutes would be outperformed for a local area of ≈ 340 km for 10 % penetration and an area of ≈ 40 km for 2 % penetration.

The results are also in good accordance with the approximation for the speed of information dissemination derived in the previous chapter, e.g. in Figure 5.7(a). However, for higher penetration ($\gamma = 0.10$), the expected delay is exceeded. This can be contributed to the assumption of an idealized communication with unlimited bandwidth and no data packet collisions for the approximation.

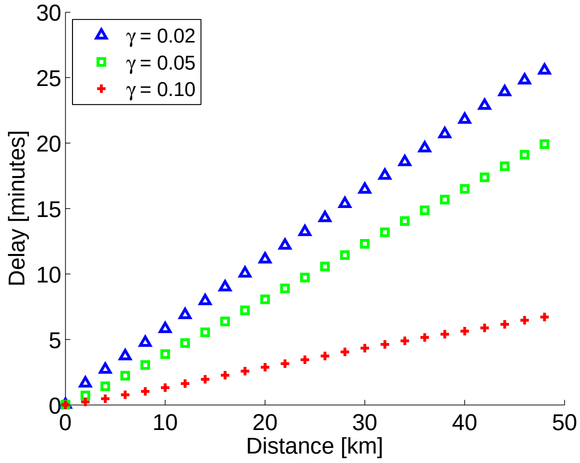
Figure 6.5(a) and Figure 6.5(c) illustrate the effect of lower and higher traffic density on the delay, respectively. In case of a low traffic density, the delays for a market penetration of 5 % and 10 % increase significantly. This is due to the fact that the chance for a communication partner in transmission range decreases. Therefore, the information is less often forwarded using the air interface – the share of transport onboard vehicles increases. For very low penetration, this way of transport is already dominating, the delay increases only slightly. A similar effect occurs for high traffic densities: In this case, the delay for scenarios assuming a high SODAD penetration is mainly caused by the time between two consecutive broadcast transmissions, thus it is only slightly reduced with a higher traffic density. Another contrary effect in case of high traffic densities is that the average velocity of a vehicle decreases (by approx. 10 % compared to a low density for the simulated scenarios).

The performance results in these road scenarios demonstrate that the system is able to provide information for the local area of the vehicle even if only a low penetration of 2-3 % is assumed. Compared to conventional multi-hop communication, much larger information ranges can be achieved: e.g. for a comfort application such as a traffic information system an information range of more than 50 km is possible even in cases of low penetration.

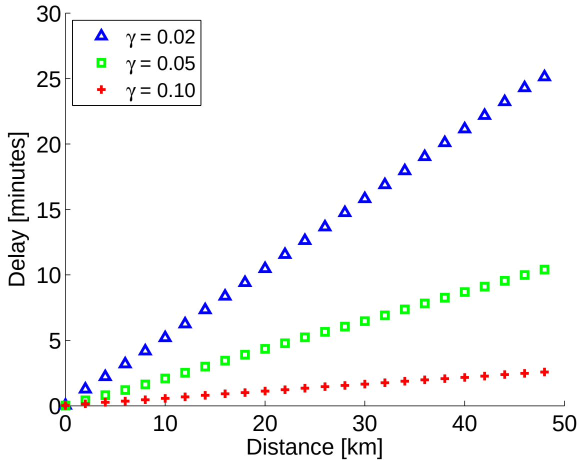
It is also important to note that due to the push communication (see Sec. 3.7.1) applied in the SODAD scheme, a delay of T minutes does not imply that the driver has to wait T minutes until he receives traffic information for a segment. Instead, it means that in average the information (which is constantly available on board the vehicle) has an age of T minutes.

6.3.5 Influence of Vehicular Traffic Model

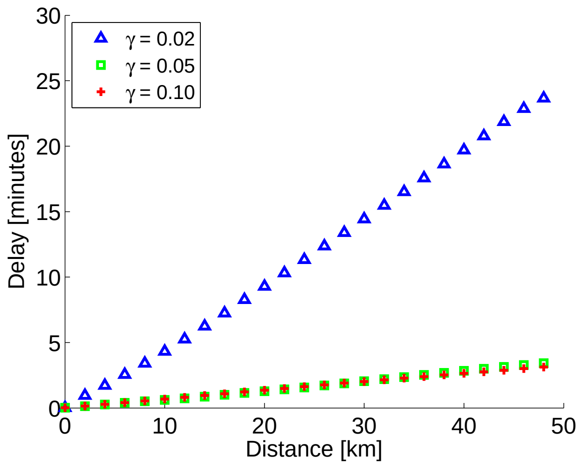
The cellular automaton based vehicular traffic model used in the simulations is parameterized by the deceleration probability p. In order to investigate the sensitivity of the simulation results to different values of p, a constant scenario is



(a) Low traffic density (7.5 veh/km/lane)

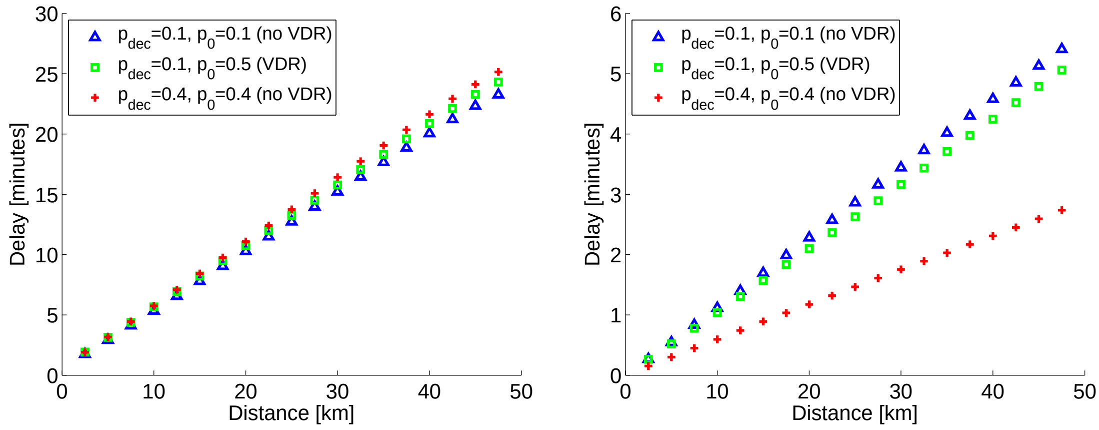


(b) Med. traffic density (10.0 veh/km/lane)



(c) High traffic density (15.0 veh/km/lane)

Figure 6.5: Performance of the basic SODAD system for a penetration of 2 %, 5 % and 10 % when the traffic density is varied. ($R = 1000$ m, two-way ground model)



(a) 2 % equipped (b) 10 % equipped

Figure 6.6: Performance of the basic SODAD system for different values of the deceleration probability in the vehicular traffic model. ($R = 1000$ m, two-way ground)

evaluated where only the characteristic of p is varied. It consists of a single highway scenario with two lanes per direction and a length of 120 km. A traffic density of 10.0 veh/km/lane is assumed, the communication parameter values are identical to those of Scenario A (Table 6.2).

In addition to a velocity-independent deceleration probability model, a Velocity-Dependent Randomization (VDR) (details in A.3.1) is introduced. In this case, the deceleration probability for a stopped vehicle is set to $p_0 = 0.5$, compared to a deceleration probability of $p_{\text{dec}} = 0.1$ for a driving vehicle (parameter values are based on observations reported in [PHC$^+$03]).

The result is illustrated in Figure 6.6. It can be observed that for a low density of equipped vehicles (Figure 6.6(a)), the influence of the deceleration parameter is low. This can be explained by the fact that physical transport via the opposite lane dominates – as already known from the previous section. Thus, the small decrease for higher deceleration probabilities is most likely due to a lower speed of physical transport.

For a higher penetration of $\gamma = 10\,\%$, a scenario with a high deceleration probability of 0.4 results in a lower average delay (Figure 6.6(b)). This effect is caused by a higher variation of vehicle speeds, which in case of a more connected network leads to an increased propagation speed on a lane. In the following, a scenario with VDR will be assumed (Scenario B, Table 6.4), if not noted otherwise.

Table 6.3: Communication parameters for Scenario B.

Parameter	**Value**
Radio Propagation Model	log-normal shadowing
• Path Loss Exponent	3.0
• Standard Deviation	4.0 dB
MAC Model	IEEE 802.11 (ad hoc mode)
PHY Data Rate	1 Mbit/s
Transmit Frequency	2.472 GHz
Transmit Power	15 dBm
Transmit Range R	500 m with probability 0.95 (if not noted otherwise)
Receive Threshold	adapted for reception probability 0.95 at R
Carrier Sense Threshold	adapted for sense probability 0.95 at $2\,R$
Capture Threshold	10.0

Table 6.4: Traffic simulation parameters for Scenario B.

Parameter	**Value**
Total Road Length	120 km
Number of Lanes	2 per direction
Deceleration Probability	VDR: $p_{\mathrm{dec}} = \begin{cases} 0.1, & \text{velocity} > 0; \\ 0.5, & \text{otherwise.} \end{cases}$
Constitution of Traffic	15 % slow, 85 % regular vehicles
Desired Velocity	108 km/h (slow), 142 km/h (regular)
Traffic Density	10 veh/km/lane
Mean Velocity	109 km/h

6.3.6 Influence of Radio Channel Model

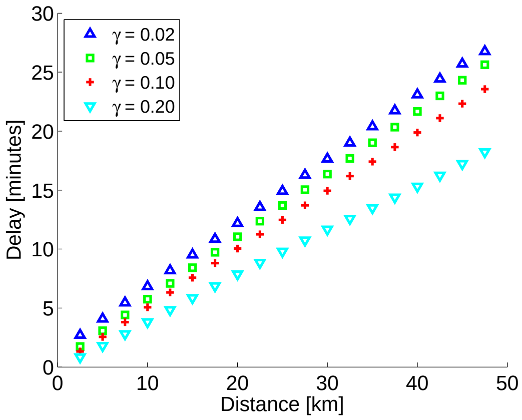
In a simulative evaluation of a wireless communication system, the modeling of the wireless channel strongly influences the system performance. While in the evaluation of MANETs the deterministic two-ray model (Sec. 3.4.2) is commonly used, a typical non-deterministic model for wireless channels is to assume log-distance path loss with log-normal shadowing (Sec. 3.4.4). Non-deterministic channel models reflect the fact that in reality the achieved communication range is also influenced by many (random) factors. Besides the channel model, the characteristics of the wireless system such as receiver sensitivity determine the achieved transmission range.

Therefore, the performance of the basic SODAD scheme is investigated for the two-ray and the shadowing channel models with a varying transmit range R. For the log-normal shadowing model, the transmit range R is commonly defined as the range which is achieved with a probability of 0.95, i.e. with a probability of 0.95 the received power at distance R is equal to or larger than the power required for successful reception (without interference). The remaining parameters are chosen according to Table 6.3. For the vehicular traffic model, the parameters of Scenario B (Table 6.4) are used, which include VDR.

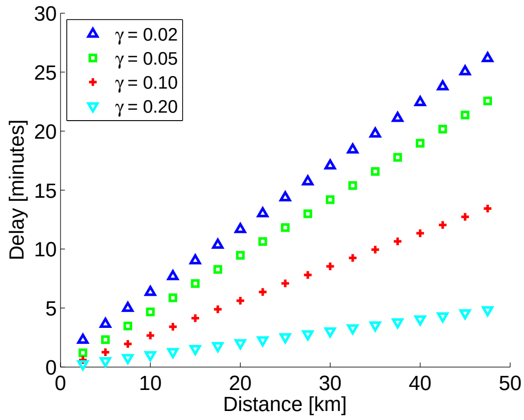
The resulting delays are illustrated in Figure 6.7. As expected in the analytical considerations in Section 3.7, the transmission range R has a high influence for both propagation models. For the deterministic model, doubling the distance R results in a similar delay as doubling the penetration γ, as illustrated in Figures 6.7(c) and 6.7(e). (Due to VDR, the resulting delays for the two-ray model in Figure 6.7(e) are slightly higher than those illustrated in Figure 6.5(b), which additionally confirms the observations reported in the previous section.)

Comparing the two channel models, SODAD in the log-normal shadowing model constantly achieves an equal or lower delay than in the two-ray ground model. The reason is that even a small chance of achieving a larger transmission range improves the performance significantly due to the large differences in the speed of information dissemination (Section 3.7): If the information is transported onboard the vehicle, the velocity is in the order of 20-40 m/s. Forwarding via the wireless link can achieve velocities larger by two orders of magnitude.

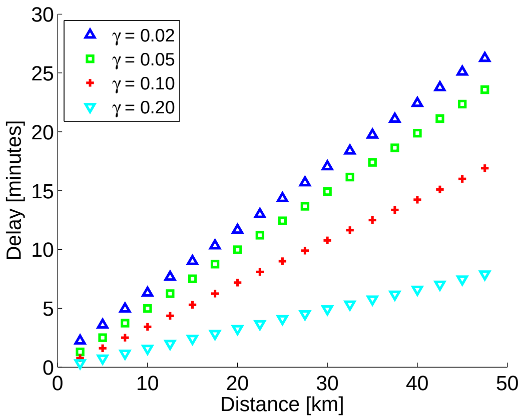
While loosing a data packet because of a bad channel usually does not have a high influence since identical or similar information is transmitted in the next packet,



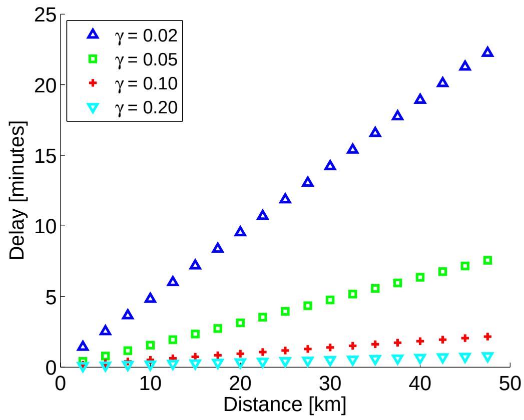
(a) Two-ray model, $R = 250\,\mathrm{m}$



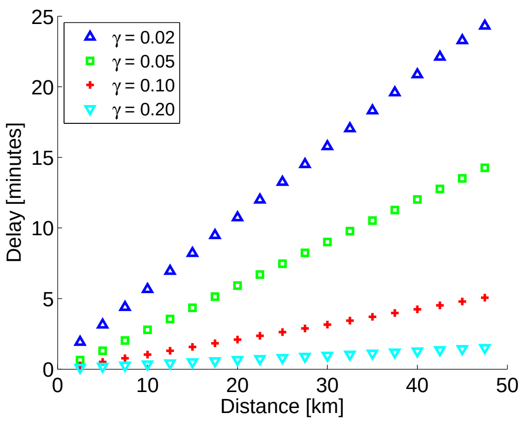
(b) Log-normal shadowing model, $R = 250\,\mathrm{m}$



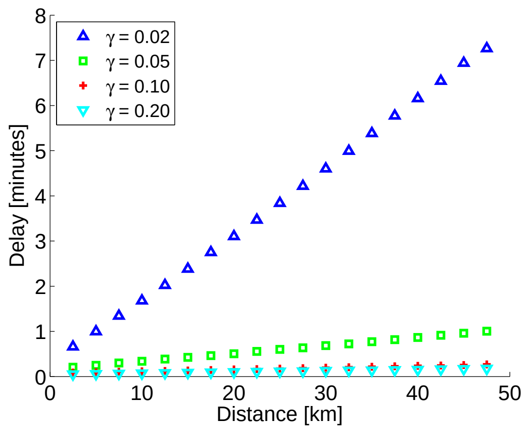
(c) Two-ray model, $R = 500\,\mathrm{m}$



(d) Log-normal shadowing model, $R = 500\,\mathrm{m}$



(e) Two-ray model, $R = 1000\,\mathrm{m}$

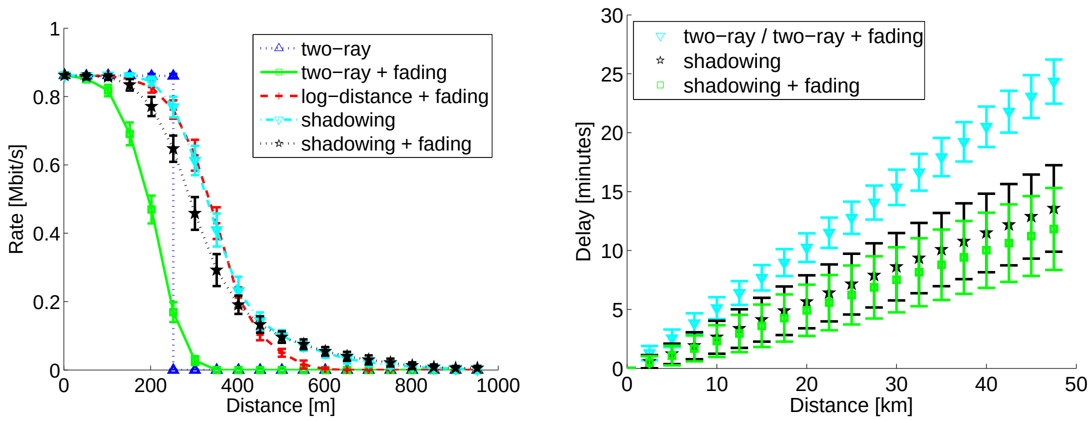


(f) Log-normal shadowing model, $R = 1000\,\mathrm{m}$

Figure 6.7: Influence of the radio model and the transmission range R on the SODAD performance. (traffic density $\rho = 10\,\mathrm{veh/km/lane}$)

a temporarily good channel (i.e. range exceeding R) can result in a drastically reduced delay – most significantly for higher penetration values ($\gamma > 0.02$). For very low values of γ, the channel model does not have a significant influence since communication occurs mainly between opposite lanes at low distances. In this case, a relevant gain due to a temporarily good propagation situation in the log-normal model is unlikely.

In the majority of this thesis, a basic assumption is that an adequately designed physical layer is used that takes the characteristics of the channel (in particular frequency selectivity and time-variance, see Sec. 3.4.5) into account. In order to illustrate the effect of highly variable channel conditions, the results of additional simulations with a Ricean flat fading model [PNS00] are shown in Figure 6.8. The Ricean factor K is assumed to be 6 dB, based on the observations in [Mau05] for a NLOS inter-vehicle communication scenario.



(a) Point-to-point data rate ($R = 250$ m) (b) Delay variance ($R = 250$ m, $\gamma = 0.10$)

Figure 6.8: Influence of the radio model on delay and point-to-point data rate.

Figure 6.8(a) plots the resulting point-to-point MAC layer data rates for the deterministic two-ray, log-distance with 4 dB log-normal shadowing (path loss exponent 3.0), log-distance with added Ricean fading, log-distance with shadowing and fading, and two-ray with fading models. Error bars indicate an interval of plus/minus standard deviation. It can be observed that fading increases the variance of the achieved data rate for all models.

The effect on the SODAD scheme is shown in Figure 6.8(b). In general, the variance of the delay for information dissemination also increases. For the deterministic two-ray model, this effect is negligible – mean delay and variance are quasi identical. This indicates that the variance in dissemination delay in this case stems from the randomness of the traffic simulation rather than from the non-deterministic radio channel behavior. In contrast for the log-normal shadowing model including fading, the delay is reduced. In the flat fading model, situations of constructive interference enable wireless data forwarding over larger hops resulting in a faster dissemination, whereas destructive interference is mitigated by the high level of redundancy. Analogously to the comparison of the two-ray with the shadowing model, a higher variability of the transmission range is beneficial for the SODAD scheme.

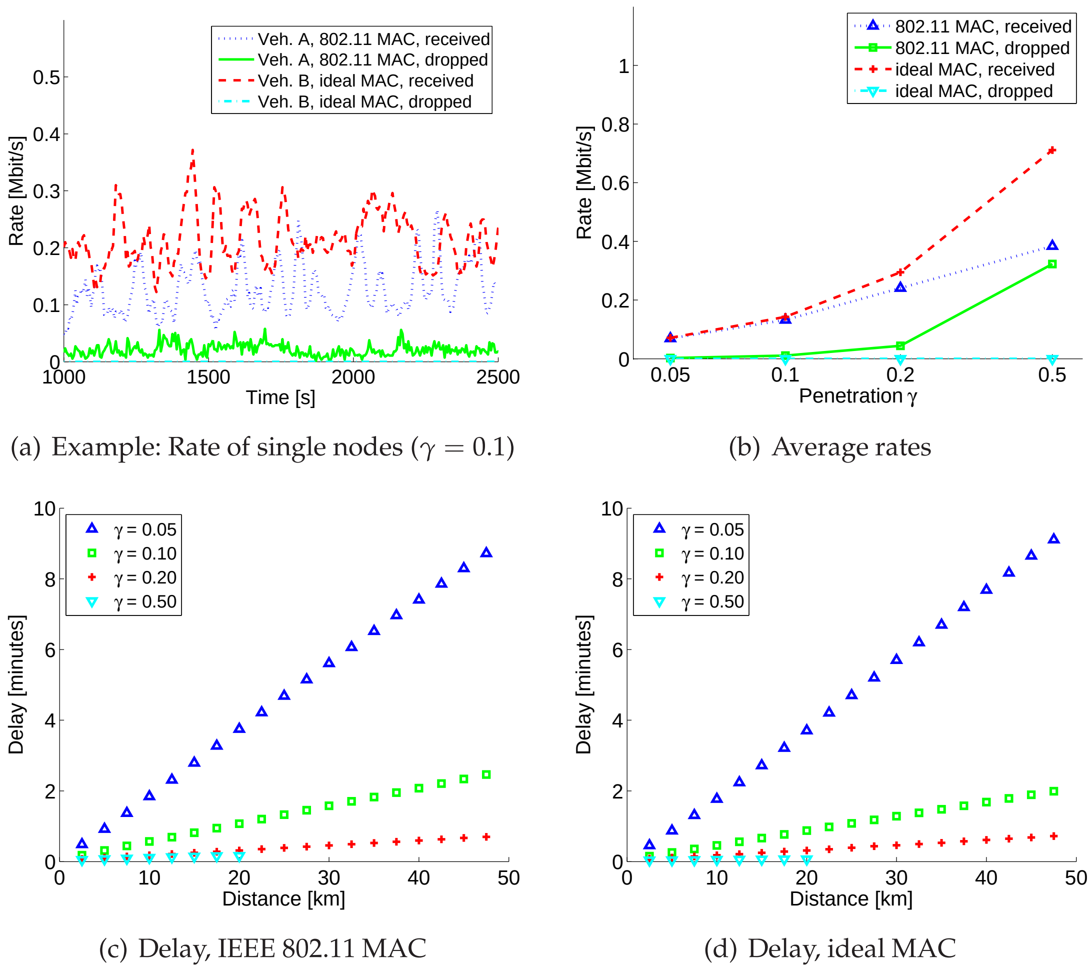
6.3.7 Influence of MAC Protocol

In general, the medium access protocol assumed in this thesis is a TDMA protocol such as the IEEE 802.11 MAC (Section 3.5). Although a similar MAC (IEEE 802.11p) will likely be used in future VANETs, it is well known that the IEEE 802.11 MAC has severe deficiencies in an ad hoc communication scenario [XS01]. A related question is to which extend the performance of an application using the SODAD mechanism is influenced by this non-ideal MAC.

Therefore, an *ideal MAC* has been implemented in the network simulator for comparison. For this ideal MAC, it is assumed that medium access is perfectly coordinated and any data packet collisions can be completely avoided, i.e. a data packet is always received successfully if the signal power at the receiver exceeds the reception threshold.[2] Thus, the performance of the ideal MAC establishes an upper bound. Vehicular traffic model and communication system parameters are again chosen according to Scenario B (Tables 6.3 and 6.4).

Figure 6.9(a) shows an example for the rates at which data is successfully received and dropped due to collisions for the IEEE 802.11 MAC (Vehicle A) and for an ideal MAC (Vehicle B). It indicates that even at this relatively low penetration of $\gamma = 10\%$, a significant number of data packets is lost due to data packet collisions if the IEEE 802.11 MAC is assumed. The figure also illustrates the high dynamic in the VANET – depending on the vehicular communication situation the rate of received data is highly variable. With increasing penetration γ (i.e. increasing contention for

[2] Even parallel reception of multiple data packets can occur. As a result, a realistic MAC will always perform worse than this ideal MAC, even if it can also completely avoid collisions.



(a) Example: Rate of single nodes ($\gamma = 0.1$)

(b) Average rates

(c) Delay, IEEE 802.11 MAC

(d) Delay, ideal MAC

Figure 6.9: Influence of the MAC protocol on the SODAD performance.
For $\gamma = 0.50$, the length of the simulated road is reduced to 40 km instead of 120 km in order to limit the simulation time. Thus, only delay values for distances up to 20 km are plotted.

the wireless channel), more packets are lost due collisions as shown in Figure 6.9(b), since it is assumed for this scenario that vehicles send data at a constant rate of 2 packets per second. In case of the ideal MAC, the number of dropped packets is zero independent of γ since it avoids all packet collisions.

Interestingly, as indicated when comparing Figure 6.9(c) and 6.9(d), the resulting increase in delay for the SODAD technique is low. Again, this can be contributed to the high level of redundancy in the wireless network. The main result of these MAC investigations is therefore that for SODAD in general, improving the medium access protocol will not have much influence on the achieved performance at the application layer.

In the following, a 802.11 like CSMA protocol is assumed. However, the presented technologies are independent of the MAC protocol and could also be applied if a different MAC protocol would be used, e.g. a reservation based MAC as proposed with the Extended Self-Organizing Time Division Multiple Access (E-SOTDMA) MAC in [Ebn05a]. Such a more complex MAC protocol can avoid most data packet corruptions due to collisions and achieve a high rate of successful transmission even at high market penetration.

6.4 A Heuristic Approach to Adaptive Data Dissemination

Until now, the considered basic broadcast scheme was static: Broadcast messages were generated at constant intervals and the transmission range/transmission power of the vehicle was assumed to be fixed. Overload conditions were not actively avoided – their effect was simply mitigated by the high level of redundancy due to the periodic repetition of the broadcast messages.

In this section, this basic SODAD scheme is extended with a heuristic approach for dynamic adaptation of the broadcast interval in order to actively avoid overload conditions and favor the propagation of significant changes. In addition, it drastically reduces the average data rate required by the SODAD scheme.

6.4.1 Requirements for Adaptive Data Dissemination

Adaptive information dissemination in the considered vehicular ad hoc network is a challenging task: The environment is highly dynamic (relative velocities of up to 400 km/h) and the density of vehicles can vary from 1-2 vehicles per kilometer in low density night traffic to more than 100 veh/km/lane in traffic jam situations. These node densities can change completely within seconds, e.g. at an intersection of an empty and a crowded highway.

Whereas in low density situations a large transmission range is advantageous, in high density situations it leads to a decrease of the available transmission bandwidth for an individual vehicle. Analogously, in low density situations a short inter-transmission interval is beneficial, but it can lead to overload conditions in situations of high density.

Basically, the following methods could be used to solve this problem:

- adaptation of the transmission range (power control) [ARP05, TMSH05],
- adaptation of the inter-transmission interval and
- combined approaches.

Power control is mainly of interest for (safety) applications which need to disseminate information only in a near local neighborhood, which is smaller than the maximum transmission range. In this case, reducing the transmit power in high density situations can reduce the load on the wireless channel [TMSH05].

In contrast, for applications which disseminate information in range of multiple times the transmission range, power control does not lead to a spacial reuse gain since in a typical highway situation, information is forwarded along a line. Thus, power control results in a higher number of required transmissions for forwarding the data and cannot reduce the load. Therefore, in this thesis the focus is on the adaptation of the inter-transmission interval which is suitable for both types of applications.

6.4.2 Proposed Adaptation Procedure

The heuristic approach for the adaptation of the transmission interval, called *Provoked Broadcast* in the following [WER+03a], adapts the inter-transmission interval to the local environment and knowledge gained from received packets in order to

- reduce the delay with which information is propagated,
- favor the propagation of significant changes,

- avoid redundant transmissions and
- occupy less bandwidth in cases of congestion.

It has therefore additional properties beyond a pure reduction of the contention on the vehicular communication channel as considered in [XB04].
The basic idea of the Provoked Broadcast scheme is the following: A default inter-transmission interval T_{upd} is chosen small enough to recognize a vehicle passing by at the maximum relative velocity. If a maximum relative velocity of 500 km/h and a transmission range of 1000 m is assumed, an interval of 5 s is sufficient. This default interval is adapted according to two kinds of observed events:

1. **Provocation:** A *provocation* is an observed event that reduces the time that elapses until the next broadcast packet is transmitted.
2. **Mollification:** A *mollification* is an observed event that increases the time that elapses until the next broadcast packet is transmitted.

Examples for provoking and mollifying events, which will also be used for simulations (Section 6.4.3), are listed in Table 6.5. This dynamic adaptation of the inter-transmission interval delays redundant or less important information in cases of congestion. But if the link has been idle for a relatively long time, even information of low significance will be transmitted. This allows to use the available bandwidth in a more optimal way than a simple specification of a static level of significance below which information will always be discarded as in [GIO04].

6.4.2.1 Parameters of Adaptive Broadcast

Upon the reception of a data packet, its content is examined in order to update the vehicle's knowledge base (SODAD). Furthermore, it is determined if a provoking or mollifying event has occurred: Based on the per-segment comparison of the received data with the information available in the knowledge base, a weight $w_{m,n}$ of a received message m at node n is calculated. It indicates the discrepancy of the received per-segment data compared to the node's previous knowledge. The decision if an information value is significantly newer or different than the previously available information is based on two threshold values: If the difference of the two time-stamps exceeds the threshold ΔT_{th}, $w_{m,n}$ is increased by a constant q_{date} (the

Table 6.5: Examples for provoking and mollifying events.

Examples for Provocations

Event	**Intention**
Reception of information being out-of-date	Transmitting vehicle needs updated information
Reception of packet with significant new information	Favor propagation of changes
Reception of information from vehicle with large distance	Favor large hops in propagation
Indication (e.g. by lower layers) of excessive bandwidth	Decrease delay of information propagation

Examples for Mollifications

Event	**Intention**
Reception of similar/up-to-date information from nearby	Avoid redundant transmissions
Indication that number of received packets exceeds threshold	Limit maximum used bandwidth

so-called date quantum). Analogously, if the difference of the two information values exceeds the threshold ΔI_{th}, $w_{m,n}$ is increased by q_{info}.

Thus, the weight of a received message composed of information values for S distinct segments with IDs $i_1, \ldots, i_S$ is calculated as

$$w_{m,n} = \sum_{k=i_1,\ldots,i_S} w_{\text{info}}(s_{m,k}, s_{n,k}) + w_{\text{date}}(t_{m,k}, t_{n,k}) \tag{6-4}$$

where

$$\begin{aligned} w_{\text{info}}(s_{m,k}, s_{n,k}) &= \begin{cases} q_{\text{info}} & : \ |s_{m,k} - s_{n,k}| \geq \Delta I_{\text{th}} \\ 0 & : \ |s_{m,k} - s_{n,k}| < \Delta I_{\text{th}} \end{cases} \\ w_{\text{date}}(t_{m,k}, t_{n,k}) &= \begin{cases} q_{\text{date}} & : \ |t_{m,k} - t_{n,k}| \geq \Delta T_{\text{th}} \\ 0 & : \ |t_{m,k} - t_{n,k}| < \Delta T_{\text{th}} \end{cases} \end{aligned} \tag{6-5}$$

Again, the values $t_{m,k}$ indicate the time-stamp for segment k in message m and $t_{n,k}$ the time-stamp for segment k in the knowledge base of node n. Analogously, $s_{m,k}$ and $s_{n,k}$ are the respective information values for segment k.

A message will be assigned a high weight $w_{m,n}$ if it was transmitted by a node that has significantly different information for the respective segments. In contrast, a low weight means that the node which broadcasted this message has a very similar view of these segments. In the following, it is assumed that the constants q_{info} and q_{date} are chosen in a way that $S \cdot (q_{\text{info}} + q_{\text{date}}) \leq 1$ and therefore the weight of a message is in the interval $[0, 1]$.

6.4.2.2 Provoking and Mollifying

Based on the weight of a received message, a node determines if a provocation or mollification has occurred: Reception of a message with a weight less than the mollification weight w_{mol} causes an increase of the remaining time by Δt_{mol} until the next transmission of a traffic analysis for the respective road segments; reception of a message with a weight larger than the provocation weight w_{prov} decreases this time by Δt_{prov}. Both values can either be chosen as absolute times or relative to the currently remaining time until the next transmission. Figure 6.10 illustrates the reaction to the two different types of events.

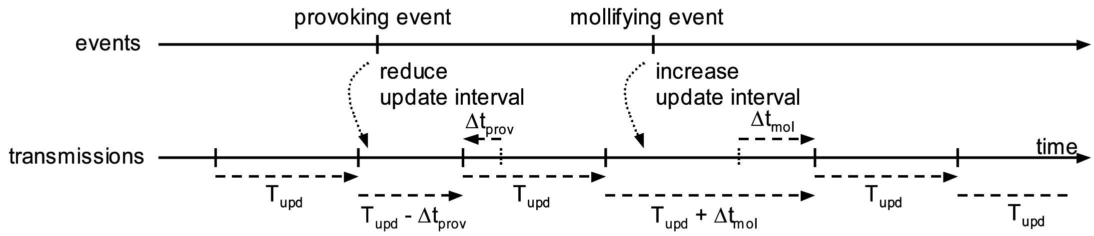


Figure 6.10: Adaptation of the inter-transmission interval.

In general, the grade in which the current interval is adapted should correspond to the weight, e.g. a high weight (≈ 1) should cause a more significant adaptation of the interval than a weight just slightly larger than w_{prov}. A detailed explanation of the parameters used is given in Section 6.4.3.

6.4.2.3 Interdependence of Provoking and Mollifying

Boundary condition for the outlined self-organizing system is that the bandwidth is limited. One approach is to use the event that the desired network load is exceeded as a mollification. However, in many cases this is not necessary due to the interdependence of provoking and mollifying events outlined in the following example: A cluster consists of M individual nodes, which are all in transmission range of each other. Since the nodes are at a similar physical location, they will have a similar view of the surrounding environment. Now, an approaching node transmits a data packet with significantly new information. The weight computed in each of the receiving nodes will therefore be high and all will reduce the remaining time until their next transmission. However, since the nodes are not synchronized, one of them will transmit first. When the $(M-1)$ other nodes receive this data packet, a low weight is assigned (since all have similar information) and a mollification is caused. Therefore, the provocation caused by the approaching node causes only one transmission immediately after the reception. An interesting question – which will be considered next – is, which of the M nodes in the cluster should perform this transmission.

6.4.2.4 *Influence of Distance*

In a self-organizing network based on broadcast messages, it is common sense that favoring large hops in the propagation of information can be used to reduce the required bandwidth. Furthermore, nodes at a larger distance are more likely to be out of transmission range in the near future. Therefore, a distance quantum q_{dist} is calculated, depending on the distance d_{tx} to the transmitting node

$$q_{\text{dist}}(d_{\text{tx}}) = \begin{cases} 0 & : \; d_{\text{tx}} < D_{\text{th}} \\ \frac{d_{\text{tx}}}{d_{\text{tx,max}}} & : \; d_{\text{tx}} \geq D_{\text{th}} \end{cases} \qquad \text{(6-6)}$$

where $d_{\text{tx,max}}$ is the maximum transmission range, d_{tx} is the distance of the node that transmitted the message (calculated using position information in the packet header) and D_{th} is a threshold. If $q_{\text{dist}} > 0$, a provocation is caused. Therefore, more distant nodes are more likely to transmit next. Since their transmissions will cause mollifying events for the other nodes in transmission range, large hops are favored in the propagation of information. (A similar influence of the distance is the basis of recently proposed beaconless or contention-based geographic forwarding algorithms [HBBW04, FWK+03].)

6.4.2.5 Potential Risks

A potential disadvantage of the proposed scheme is that in cases where a strong provocation (i.e. reception of a packet with $w \approx 1$) occurs within a cluster of nodes, the nodes will collectively reduce their remaining time until next transmission. This can increase the data packet collision rate slightly. However, a suitable MAC protocol (e.g. reservation based) can be used to avoid this risk – and furthermore, the simulations indicate that even if the scheme is used on top of a standard 802.11 MAC, the rate of collisions is low.

6.4.3 Performance Evaluation

For performance evaluation, a simulation of the vehicular ad hoc network analogous to Section 6.3 is conducted. The same communication and road traffic parameters (Tables 6.3 and 6.4) are used. For all scenarios a penetration rate of 10 % and a traffic density of 10 veh/km/lane is assumed.

Table 6.6 lists the values assumed for the system parameters introduced in Section 6.4.2.1: The main parameter varied is the default inter-transmission time T_{upd}. For simplicity, all simulations presented here assume the same info and date quanta of 0.200 and 0.100, respectively. In combination with the threshold values ΔI_{th}, ΔT_{th} and the weights w_{prov} and w_{mol}, they determine how fast the adaptation of the inter-transmission interval is performed. (A more comprehensive evaluation including varying values for q_{info} and q_{date} has been published in [WER+03a]. In general, the scheme is not very sensitive to changes of these parameter values.)

The values for Δt_{prov} and Δt_{mol} by which the currently remaining time t until the next packet transmission is adapted (Section 6.4.2) are calculated as follows: In case of a mollification, the remaining time until next transmission is increased by 1 s, in case of a provocation, the remaining time is multiplied by $(1 - q_{\text{dist}})(0.5 - w)$. The inter-transmission time resulting from a single adaptation is limited to the interval $[0.001T_{\text{upd}}, 2T_{\text{upd}}]$ in order to avoid extremely low or high rates. For the periodic scenarios, the data rate of each node is varied from 0.2 to 4.0 packets per second per node.

The required bandwidth for the adaptive broadcast scheme depends on the data to be distributed. In order to have a worst case estimate, a uniform distribution of the

Table 6.6: Parameters for the adaptive Provoked Broadcast (PBcast) scheme.

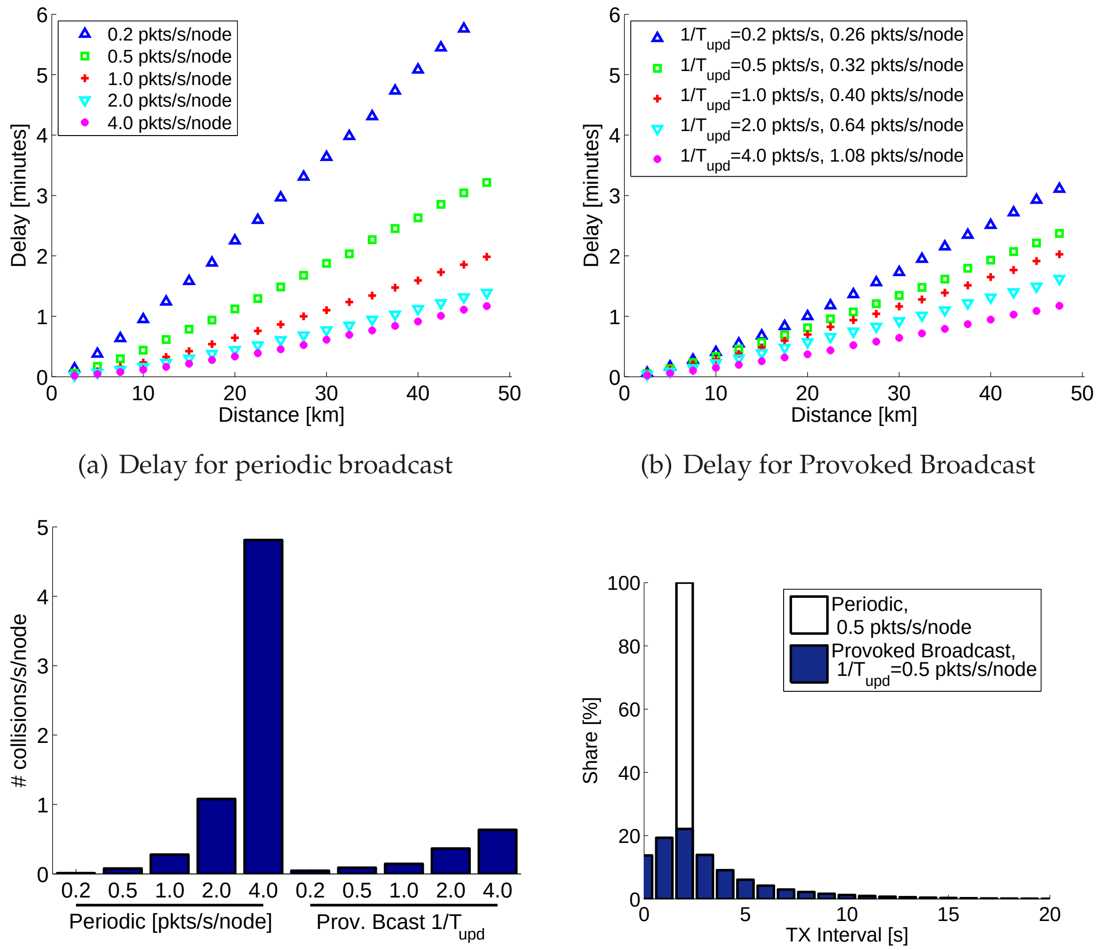
Parameter	Value
Info Quantum q_{info}	0.200
Date Quantum q_{date}	0.100
Time Threshold ΔT_{th}	20.0 s
Info Threshold ΔI_{th}	1.0
Distance Threshold ΔD_{th}	750 m
Provocation Weight w_{prov}	0.04
Mollification Weight w_{mol}	0.01
Default Inter-Transmission Time T_{upd}	0.25 s, 0.50 s, 1.00 s, 2.00 s, 5.00 s
Info Change Period T_{Ichange}	600 s

per-segment info values is assumed (maximizes entropy). Info values are updated independently and randomly for each segment with the change period T_{Ichange}.

Figure 6.11 compares the two approaches under various aspects: In Figure 6.11(a) and 6.11(b), the resulting delay for propagating new information is plotted. For the periodic broadcast, the average delay decreases with increasing number of packets transmitted. Increasing the rate to more than 2 pkts/s/node does not decrease the delay significantly for the evaluated scenario.

In the adaptive case, a default interval of $T_{\mathrm{upd}} = 5\,\mathrm{s}$ results in an average rate of 0.26 pkts/s/node and achieves a performance comparable to a strictly periodic broadcast with 0.5 pkts/s. In general, the required data rate for a specific average delay can be reduced significantly compared to a non-adaptive broadcast. For example, in case of $T_{\mathrm{upd}} = 0.25\,\mathrm{s}$, the performance of a periodic broadcast with a rate of 4.0 pkts/s achieved with an average rate of only 1.08 pkts/s. Thus, the required data rate is reduced by ≈75 % in this case.

The adaptive scheme also leads to a much lower rate of packet collisions as shown in Figure 6.11(c), even for this relatively low penetration of $\gamma = 0.1$. This is due to the fact that Provoked Broadcast reduces the load on the medium in case of a high density of nodes. A histogram of the inter-transmission intervals (Figure 6.11(d)) illustrates that even quite large intervals can occur – about 44 % of the intervals exceed 2 s for a default inter-transmission interval of 2 s. This is due to the fact that a vehicle defers from own transmission if its information has recently been transmitted by other vehicles nearby. This advantage becomes even more important for higher VANET penetrations. Overall, the performance improvement clearly compensates the additional computational overhead introduced by the adaptive scheme.



(a) Delay for periodic broadcast

(b) Delay for Provoked Broadcast

(c) Packet collisions

(d) Histogram of transmission intervals

Figure 6.11: Performance comparison of the adaptive Provoked Broadcast scheme with a periodic broadcast: delay for propagating new information, transmission intervals and collisions. (penetration $\gamma = 0.1$)

6.5 Summary of Chapter

A segment-oriented technique for abstracting and disseminating the data in a vehicular ad hoc network has been presented. For delay-tolerant applications, it can achieve an information range of more than 50 km even if only a low ratio of all vehicles is equipped with the ad hoc communication system.

The scheme has been evaluated by system-level simulations and shows the characteristics predicted by the analytical approximations derived in Chapter 3. The influence of various parameters (vehicular traffic model, radio channel model, medium access technique) on the system has been analyzed.

Afterwards, it has been shown that a simple heuristic for adapting the inter-transmission interval can avoid overload conditions, increase the speed of data dissemination and reduce the required average data rate. The issue of load control is reconsidered in detail in Chapter 8, where a more formal approach including fairness aspects is presented.

VII

Self-Generated Maps based on Vehicular Ad Hoc Communication

The SODAD approach for information dissemination in a VANET presented in the previous chapter has a major limitation: It requires identical road and segment identifiers to be available at each vehicle. This complicates the deployment, since in general it cannot be guaranteed that road maps provided by different vendors use the same identifiers.

Conventional digital road maps are usually pre-installed in the navigation system onboard the vehicle and updated in relatively large time intervals, e.g. by distributing a CD-ROM with updated map data. Storing large digital road maps on board the vehicle imposes costs for licensing map data and computing resources. In order to be able to include driver assistance technologies based on inter-vehicle communication in low end systems, it is desirable to drop the requirement of a pre-installed digital road map and allow a continuous update of map information.

Therefore, in this chapter a generalization of the SODAD approach is presented which allows vehicles to generate a road status map for the local area based on measurements received from other vehicles. The generated digital map can complement an existing digital map but does not depend on it. In particular, no global road/segment identifiers are required. In addition to geographic information, the generated map includes dynamic information measured by vehicles which characterizes the state of the road, similar to the status information disseminated in SODAD.

Potential applications for self-generated maps are manifold: Driver assistance and safety systems such as the Electronic Stability Program (ESP) can profit from the additional geographic and dynamic information on the course and status of the road ahead. For example, the knowledge about low temperature/ice at a location ahead can be used to warn the driver of potentially hazardous situations. Information cur-

rently not included in commercial maps but measurable by other vehicles can be obtained, such as height, mean velocity, curvature, etc. The generated digital map can also significantly improve the data dissemination in the VANET, e.g. for position based routing [LMFH05] or road segment oriented broadcast [WER05a].
For the proposed scheme, only the following two components are required:

1. an ad hoc capable air interface and
2. a satellite based positioning system (e.g. GPS or Galileo).

The system is completely independent of conventional digital road maps and fixed infrastructure such as base stations or sensors deployed at the roadside.
The focus in this chapter is on outlining a concept for generating a road map based on ad hoc communication and not on a detailed simulative evaluation. Since the dissemination of map related information is performed by applying the SODAD scheme, the results obtained in the previous chapter (in particular regarding the delay of information dissemination and the required VANET penetration) are also valid for the extended approach presented here.
The material in this chapter is organized as follows: Section 7.1 introduces the proposed scheme for generating maps based on vehicular communication, including the creation of map data to be transmitted (Sections 7.1.1 and 7.1.2) and the integration of received information (Section 7.1.3). In Section 7.2, the feasibility of the proposed approach is evaluated by simulation and an experimental implementation. Related work, derived possible enhancements of the proposed map-building technique and a comparison to conventional maps are given in Section 7.3.

7.1 Self-Generated Road Status Map

The basic idea of the scheme for self-generated road status maps is to exchange information between vehicles which describes the driven track [WER06]. In order to be independent of the representation of a street within a specific digital map, the segmentation of a road known from Chapter 6 is replaced by a two-dimensional segmentation using a global reference grid.
By combining the information obtained from all vehicles in transmission range, a digital map of the local area is created. It includes position and status information and allows a driver assistance system to perform a situation analysis, e.g. for the

traffic status. Since a vehicle continuously transmits parts of its own locally generated map, track information is exchanged over multiple hops and the generated road map covers a distance much larger than the transmission range of an individual vehicle. (Analogously to the dissemination of per-segment information in SODAD over multiple hops.) A vehicle stores and updates only information for the relevant local area, therefore the required computing resources are low.

The information on the driven track is recorded in form of Geo-Reference Points (GRP), which describe the condition at a specific location. Multiple GRPs for a road are combined to form a Geo-Reference List (GRL). Since a GRL describes a connected track segment, it can be efficiently encoded and broadcasted to vehicles nearby.

In particular, the following steps are performed by each vehicle periodically:

1. generating GRPs and inserting them in the own local map,
2. creating, encoding and broadcasting GRLs,
3. integrating received GRLs in local map.

These three steps of sensing, transmitting and receiving status map information are described in detail in the following.

7.1.1 Generating the Geo-Reference List (GRL)

A GRL describes a connected track segment (e.g. part of a road traversed by the vehicle) by consecutive geo-reference points. For generating these GRPs, a global geodetic reference grid is used. It serves three purposes:

- *unambiguous representation* of a road by GRPs (within positioning inaccuracy D_{acc}, which depends on the accuracy of the positioning device. For a typical GPS receiver, D_{acc} is in the order of 10-50 m.),
- *avoiding positioning error propagation* when integrating received GRPs (details in Sec. 7.1.3),
- *limiting the number of created GRPs* for a road.

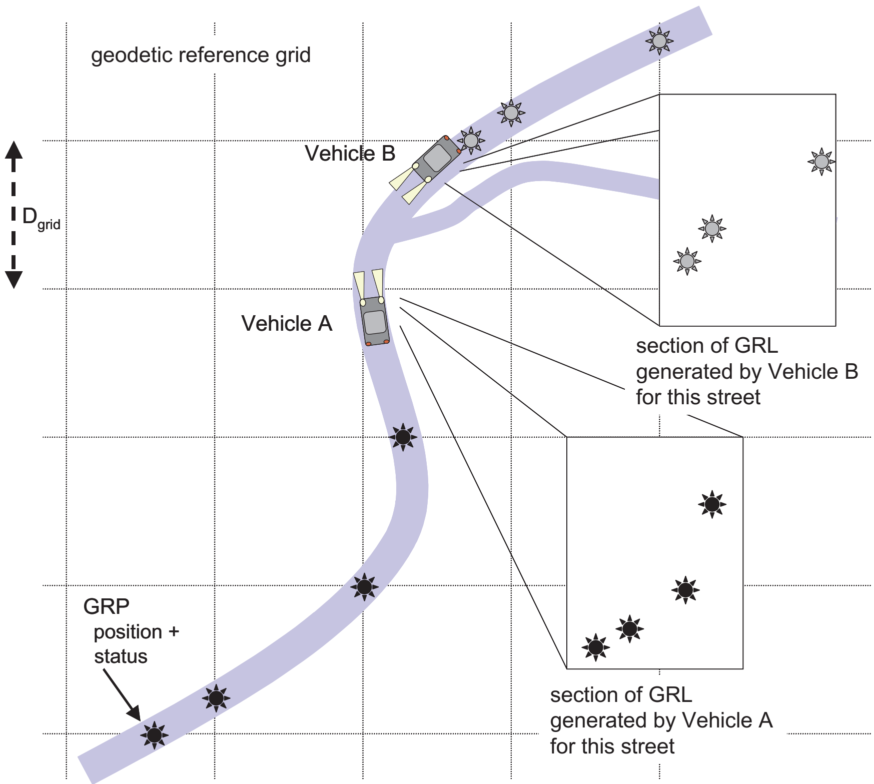


Figure 7.1: Example for generated Geo-Reference Points (GRP) and the obtained Geo-Reference List (GRL).

The reference grid is determined by the grid distance[1] D_{grid} and the point of origin. Such a grid is easily obtained by applying a transverse mercator projection, e.g. the Universal Transverse Mercator (UTM) or Gauss-Krüger coordinate system, to the geographic coordinates obtained via satellite navigation system. In the following, GPS coordinates obtained in the World Geodetic System 1984 (WGS84) are assumed and Gauss-Krüger coordinates are used for the geo-reference grid. However, the same approach can be applied with UTM and other coordinate systems.

The parameter D_{grid} determines the tradeoff between accuracy and required data rate: A smaller D_{grid} leads to a higher accuracy but also a higher data rate. Furthermore, D_{grid} should be larger than the expected position inaccuracy D_{acc} of the positioning system. As depicted in Figure 7.1, the road is now "sampled" with the resolution of the reference grid, by applying the following procedure: The vehicle continuously monitors its position. Whenever its track intersects with a line of

[1]distance between two lines of the grid

the geo-reference grid, a GRP is generated with the following exception: In order to avoid continuous generation of GRPs separated by only small distances, a GRP is *not* generated if the direction of movement differs from the direction of the respective line of the geo-reference grid by less than $\frac{\alpha}{2}$. For example, only horizontal GRPs (GRPs on horizontal lines of the grid) are generated if the vehicle moves in a direction of $180° \pm \frac{\alpha}{2}$ or $0° \pm \frac{\alpha}{2}$.

In this way, a minimum angle is guaranteed for any GRP resulting from an intersection with a specific grid line. This is necessary since in case of a very low angle of intersection ($< \frac{\alpha}{2}$), a small position inaccuracy can lead to very different GRPs being generated for the same intersection with the grid line – leading to an ambiguous representation of the track. Thus, the system parameter α is related to the accuracy of the positioning: The more accurate the position of the vehicle can be determined, the lower is the minimum allowed value of α. Due to the fact that the technique is not very sensitive to the parameter α, a rather conservative value of α=30° is used in the following. Figure 7.2 summarizes the type of GRP generated depending on the direction of movement.

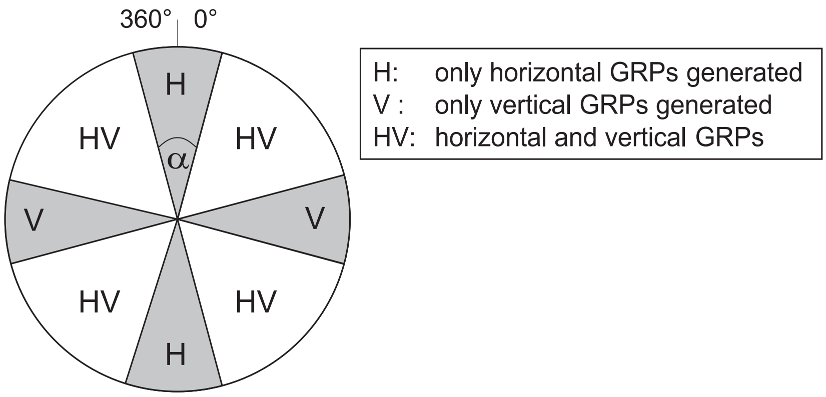


Figure 7.2: Types of GRPs depending on angle of movement.

For each newly generated GRP, the vehicle checks if it can be matched to an existing GRP of a road in the same direction in its own local map. In case of a match within the assumed accuracy of the positioning (D_{acc}), the existing GRP is updated with the currently sensed information – otherwise, the GRP is added to the map. In this case, the vehicle first tries to append it to an existing road within the map. This is only possible, if the distance to one of the existing GRPs is less than $\sqrt{2}D_{\text{grid}}$. Otherwise, a new road is inserted which has the respective GRP as starting point.

As already mentioned, multiple consecutive GRPs for a road form a GRL, the entity in which GRPs are broadcasted to vehicles. Periodically, the vehicle selects a part of its local digital map for transmission. For now, the scheduling algorithm for determining which GRPs to broadcast is out of scope and a round robin procedure is assumed for simplicity. This issue is reconsidered in Chapter 8, where a utility based scheduling technique is presented.

The selected part of the local map is converted to a GRL and broadcasted to all vehicles currently in transmission range. The GRL can consist of GRPs generated by the vehicle itself as well as GRPs that were generated by other vehicles. In this way, a dissemination of GRPs over multiple hops is achieved.

7.1.2 Efficient Encoding of a GRL

The main advantage of a GRL is that it allows an efficient encoding of geographic information since all GRPs in a GRL are colocated. This aspect is of particular importance since the available data rates in a VANET are relatively low and expected to be shared by many applications.

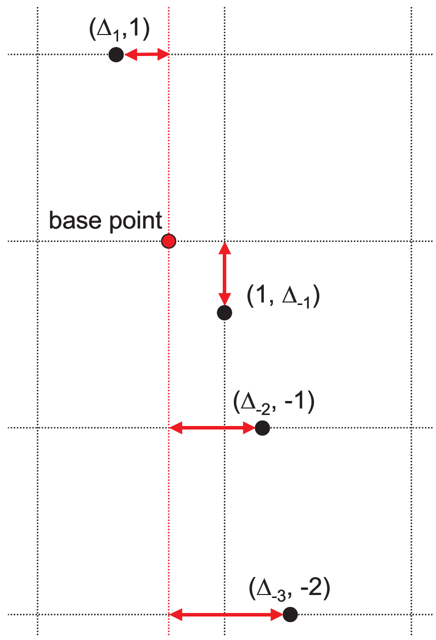
A GRL consisting of N GRPs is composed of two parts (Figure 7.3(a)):

1. a base point, which is an arbitrary GRP (e.g. at the center) of the GRL,
2. and N GRP offset specifications which describe the respective offset of a GRP compared to the base point. Since the base point as well as all GRPs are located on at least one line of the reference grid, a GRP location can be specified by a coordinate offset for one coordinate and an integer grid offset for the other. For the lowest GRP in Figure 7.3(a), the non-grid offset would be the distance Δ_{-3} indicated by the arrow and a grid offset of -2.

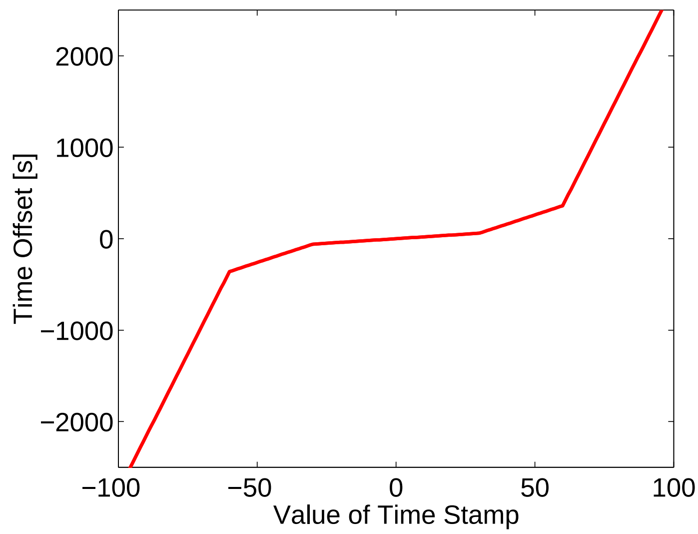
Example: Required Overhead

As an example for the required overhead, the values from an experimental implementation are considered: For the GRL base point, the absolute coordinates need to be encoded, as well as a base time stamp value (22 bytes in total). Afterwards, each GRP of the GRL is encoded by the following offset values:

- 1-bit flag indicating if it is a vertical or horizontal GRP



(a) Location offset specification



(b) Encoding of time offset in time stamp byte

Figure 7.3: Efficient encoding of geo-reference lists.

- 15-bit integer specifying the non-grid coordinate
- 1-byte grid offset for grid coordinate
- two 1-byte data offset values (one for each direction of the road)
- two 1-byte time stamp offset values (one for each direction of the road)

In order to store a time stamp offset covering a large range in a single byte, a simple companding method is used, as shown in Figure 7.3(b). It reflects the fact that for smaller time offsets a higher precision is beneficial. E.g., it encodes time offsets with an absolute value up to 60 s with a granularity of 2 s, less than or equal to 360 s with granularity 10 s and offsets up to 4000 s with granularity 60 s.

In this example, an encoded GRL consisting of N GRPs requires $22 + 7N$ bytes. Thus, in a single 1400 byte data packet, 196 GRPs can be broadcasted. Assuming a grid distance of D_{grid}=100 m and an average GRP distance of 50 m, geographic and status information for a 9.8 km road segment is transmitted within a single data packet.

Algorithm 1: Pseudocode illustrating the integration of a received GRL.

Data: Received GRL
Result: Updated local map

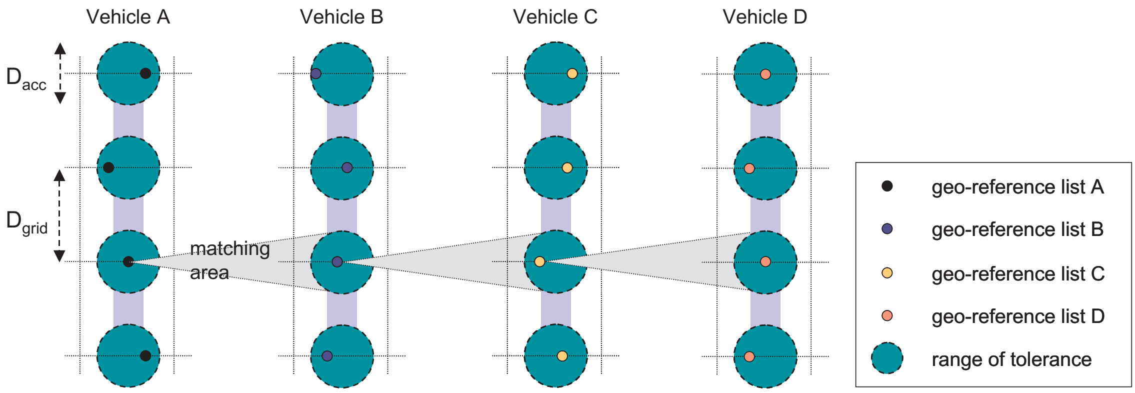
Convert GRPs of GRL to absolute coordinates;
foreach *GRP in GRL* **do**
    $\gamma \leftarrow$ `Direction`(*previousGRP*, *GRP*, *nextGRP*);
    matched $\leftarrow$ `MapMatchedPosition`(*GRP*, γ);
    if `Distance`(matched, *GRP*) $\leq D_{acc}$ **then**
        update data values for matched *with GRP*;
    else
        if *road start/end GRP within distance* $\sqrt{2}D_{grid}$ **then**
            extend existing road with GRP;
        else
            create new road with GRP;

7.1.3 Integrating a Received GRL

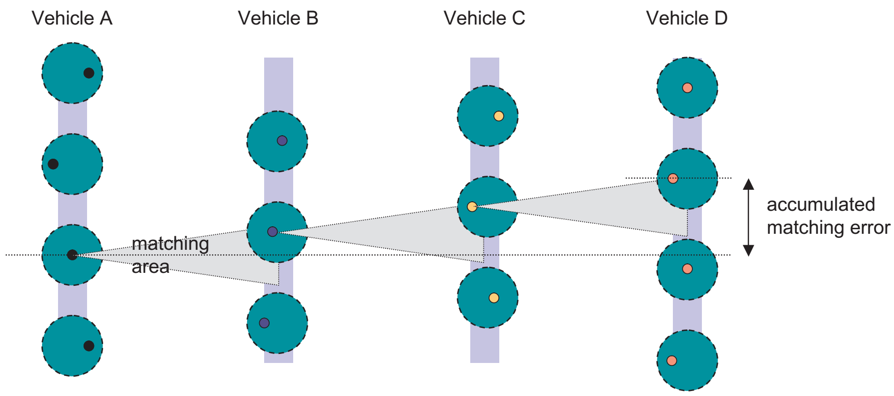
Whenever a vehicle receives a broadcasted GRL, the relative positions of the GRPs (i.e. offset values) are first converted back to absolute positions. Afterwards, each GRP is matched on the existing map. In the matching process, the direction of the GRL at the respective position needs to be taken into account to avoid matching to an incorrect road, e.g. in intersection situations. Therefore, matching only occurs on roads in direction of the GRL at the GRP.

If a matching position at a distance less than or equal to the assumed positioning inaccuracy D_{acc} and with similar direction is found, the GRP is already known. In this case, the data values of the received GRP are used to update the existing map for each direction where the time stamp is newer than the time stamp in the existing map, similar to the procedure for updating road segment values in SODAD (Section 6.2.2).

Otherwise, the received GRP needs to be added to the vehicle's local map. If an existing GRP is within a distance less than or equal to $\sqrt{2}D_{\text{grid}}$ and is also the start/end point of an existing road in a similar direction, the respective road is extended by the new GRP. If this is not the case, the GRP is added as the starting point of a new road. Pseudocode for this integration process is shown in Algorithm 1.



(a) with geodetic reference grid



(b) without reference grid

Figure 7.4: Accumulation of positioning errors is avoided by the reference grid.

It also illustrates an important property of the global geo-reference grid: An accumulation of positioning errors is avoided since data values for GRPs within D_{acc} are always matched to the same local GRP, as shown in Figure 7.4(a). If vehicles would collect equidistant GRPs without a reference grid, information exchange over multiple vehicles can result in an accumulated error exceeding D_{acc}. In the example in Figure 7.4(b), information obtained for a GRP at Vehicle A is passed via Vehicles B and C to Vehicle D. Although in each single matching process the inaccuracy is below D_{acc}, the resulting discrepancy at Vehicle D compared to the original position at Vehicle A is much larger.

The matching procedure here does not consider the side of the road on which a GRP is located. This in turn limits the achievable accuracy of the generated map, since for the two directions, GRPs with an offset of about half of the road width will be

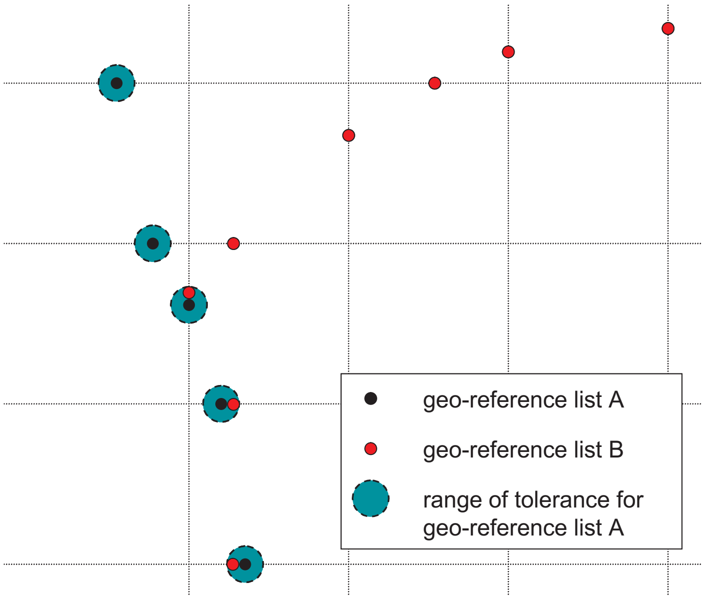


Figure 7.5: Comparing two different geo-reference lists.

observed. Although heuristics can be integrated which are aware of this fact, they are not applied in the following, for simplicity.

7.1.4 Distinguishing Different Roads

Since transmitter and receiver of a GRL can have traveled on different sequences of roads, their local assignment of GRPs to roads is not necessarily identical. Therefore, the receiver must be able to distinguish different roads in a received GRL. A simple approach is illustrated in Figure 7.5: Each GRP has a specific "range of tolerance" D_{acc}. As long as GRPs are within this range, they are considered to be part of the same road. In the example, the lower three GRPs of the two GRLs belong to the same road, the remaining ones differ.

7.1.5 Merging Roads

Depending on the order in which GRPs are received, a single road can be fragmented in the local map of the vehicle. E.g. if two disconnected parts of a road are received for a previously unknown road, the vehicle will create two separate road entries in its local map since at that time it is unknown if the parts are connected. Since for some applications the knowledge of roads is beneficial [WER05a], fragmentation needs to be limited. This could either be done by actively searching for connected roads in the local map periodically or – as it is implemented in the system used for performance evaluation in the following section – by merging two roads whenever a vehicle traverses the connection of two roads (directly moving from the end/start GRP of one road to the end/start GRP of another road).

7.2 Evaluation of Feasibility

In the following, simulative and experimental results for the scheme introduced in Section 7.1 are presented. The parameters are chosen to be identical, as listed in Table 7.1.

Table 7.1: Parameters in simulative and experimental evaluation.

Parameter	Value
Grid Distance D_{grid}	100.0 m
Assumed Position Accuracy D_{acc}	30.0 m
Angle α for H/V GRP	30.0 °
Transmitted GRLs	0.5/s
Data Rate	approx. 500 byte/s
RMSE for GPS Error Model (sim.)	0.0-20.0 m

7.2.1 Simulation

The simulation scenario considers an approx. 35 km highway segment of the A250 (Lüneburg ↔ Hamburg) in Germany. The structure for the simulative evaluation is shown in Figure 7.6: Based on digital street data read from a commercial vector map, a road pattern is created in the simulator. It is used to calculate the true simulated position of the vehicle based on a simple road traffic simulation. A random positioning error (details on GPS error model in Appendix B) is added and the resulting position is reported to the self-generating map implementation. The generated map is then compared to the ideal road data for each position of the vehicle. In the comparison, a simple linear interpolation between consecutive GRPs is assumed. It is likely that a more complex interpolation scheme, e.g. a spline interpolation, would further improve the accuracy of the generated map.

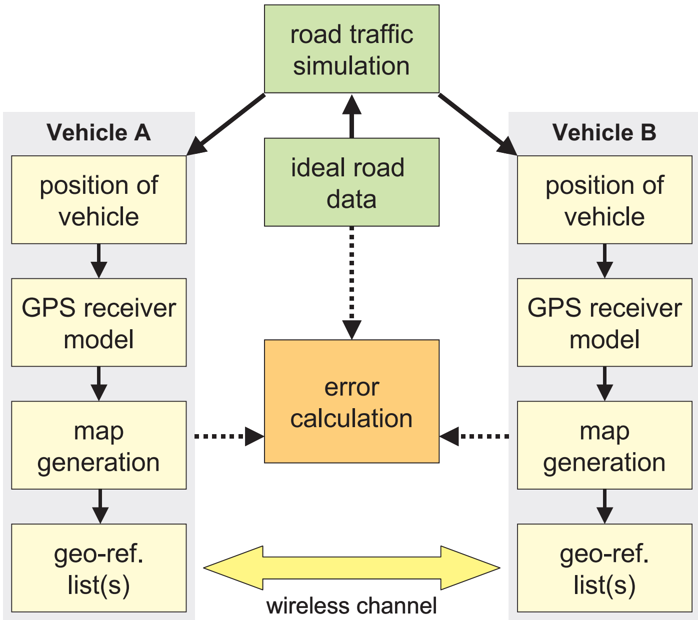


Figure 7.6: Structure of simulative performance evaluation.

These effects are out of the scope of this chapter, since they largely depend on the characteristics of the used positioning system.

Figure 7.7 shows the mean deviation of the generated map compared to the ideal map, including the 99% confidence intervals. When the Root-Mean Squared Error (RMSE, corresponding to $\sqrt{2}\sigma_{\mathrm{d}}$ in the GPS error model) increases, a corresponding increase in deviation is observed.

However, even if the positioning error is zero, the mean deviation compared to the ideal map is still $\approx$2.7 m. This is explained by the fact that the number of GRPs is limited by the grid distance D_{grid} and GRP accuracy is influenced by the encoding for transmitted GRLs (Section 7.1.2). Therefore, to further improve the accuracy of the generated map, a smaller distance D_{grid} and/or a more accurate encoding of the positions could be used. Both would lead to an increased communication overhead. Thus, the required map accuracy for a specific application needs to be considered.

7.2.2 Experimental Implementation

In addition to the simulative evaluation, the proposed map-building method is implemented in an experimental system. Standard consumer-grade GPS receivers

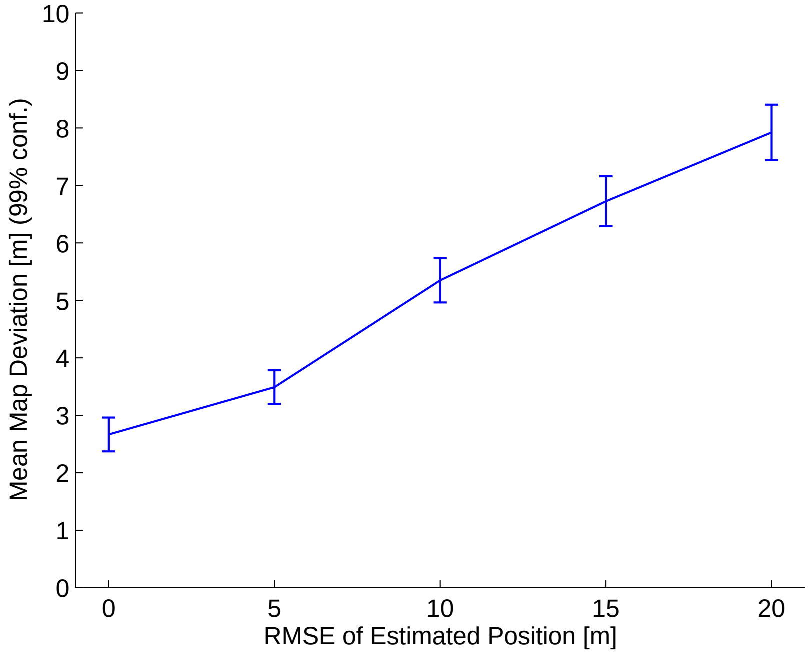
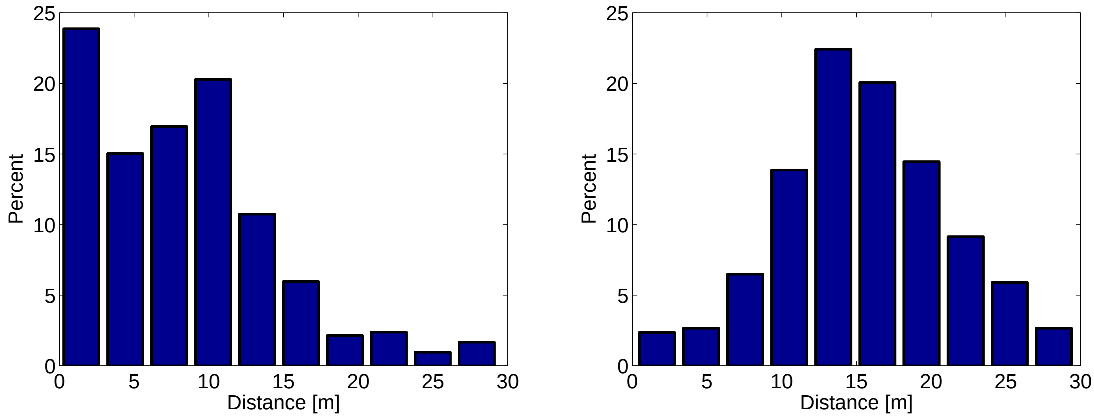


Figure 7.7: Mean deviation of generated map compared to ideal map when the RMSE of the position estimate increases. Error bars illustrate the respective 99% confidence intervals.

are used for obtaining the current position of the vehicle. The results are measured at the same highway segment of highway A250 that has been used in the simulative evaluation.

For the experimental evaluation, the map deviation cannot be easily calculated since – in contrast to the simulation – the "true" positions are unknown. Therefore, as an indicator of accuracy, the histograms of the observed distances in the integration process (Section 7.1.3) are shown in Figure 7.8.

In the comparison of GRPs generated for the same side of the road (Figure 7.8(a)), the matching distance exceeds 20 m with a probability of less than 0.1. If GRPs for the opposite direction are considered, a bias of about 15 m can be observed in the matching distance. This is approximately the distance from one side of the road to the other (assumed width of lane ≈3.75 m, with of road median ≈4 m). It indicates that the integration of heuristics to estimate and compensate this constant bias, which occurs due to positions obtained for different sides of the road, could improve the accuracy.



(a) same direction (b) opposite direction

Figure 7.8: Histograms of measured distances when matching to the same geo-reference point.

7.3 Related Work

The technique developed in this chapter combines three aspects: a simple location referencing scheme, the exchange of location/status information via ad-hoc communication and the integration of received and sensed data to build a map consisting of location and status information. While the combination of these steps to generate a road status map in VANETs is novel, the individual parts are also applied in other systems.

The challenge of location referencing without requiring an identical vector map onboard each vehicle is well known. A standard such as TMC [KM99], which is used for location referencing in traffic information broadcasted via public radio, uses a global location database in addition to the road map. It basically consists of a list of global location codes which identify specific pre-defined parts of the road network. Location referencing is therefore limited to these pre-defined locations. The TMC successor TPEG allows a more general location referencing where, e.g., references for arbitrary areas, road segments and intersection points can be generated on the fly – similarly to identifying a road track by a GRL. In the TPEG decoding process, the location reference is matched to the map onboard the vehicle and in this way, the exact location is identified. Thus, for displaying information on a map, both standards assume a pre-installed vector map onboard the vehicle.

A centralized approach for building a road map based on recorded GPS positions of vehicles is presented in [LMT+04]. Vehicles equipped with a cellular communication system report position and status information to an information center. The data is filtered, road segments are identified and a digital road map is obtained. However, the technique in [LMT+04] assumes central collection of the recorded GPS data, therefore it cannot be applied in a VANET.

Map-building based on sensor data collected by individual autonomous entities is also known from robotics, where the decentralized Simultaneous Localization and Mapping (SLAM) problem [NTDW03] considers the acquisition of a joint map of features by teams of robots. For this application, filter techniques for improving the locally estimated map by integrating received information have been investigated in large detail. For example, an often applied approach in SLAM is to use an extended Kalman filter [NTDW03] to increase the accuracy of measured features by multiple measurements of individual robots. A similar approach could be applied in the integration step (Section 7.1.3) of the method proposed in this chapter in order to further increase the accuracy of GRPs and the resulting map.

7.3.1 Comparison to Conventional Vector Maps

The simulative and experimental results demonstrate that by IVC a dynamic status map of the local area of a vehicle can be obtained. Compared to conventional pre-installed vector maps, this self-generated map is limited in several ways:

Road attributes: While the self-generated map provides the detailed course of a road, several road attributes available in conventional vector maps cannot be obtained, e.g. name and type of the road. Applications that depend on these road attributes – such as route calculation in navigation systems – will therefore still require a conventional vector map.

Coverage: A self-generated map depends on received track information collected by other vehicles. Due to the limited bandwidth, it can only be created for the local area of a vehicle, e.g. up to a distance of 50-200 km from the current position.

However, the self-generated map has also several advantages due to its self-organized decentralized map-building scheme.

No licensing costs: The self-generated map allows to implement IVC and map based driver assistance systems without licensing cost for conventional vector maps, for example in low-end systems.

Up-to-dateness: The map is continuously updated by information sensed by other vehicles. Thus, it is always up-to-date and no map updates need to be installed manually by the end user.

Dynamic status information: The most important feature of the self-generated map is that it includes dynamic status information, such as the temperature, hazard information or traffic state for each road position.

This comparison indicates that self-generated maps cannot fully replace conventional vector maps. Although they enable several map based driver assistance systems without pre-installed maps in low end systems, conventional vector maps are still required for services such as navigation. But even if a conventional map is available onboard the vehicle, the self-generated map approach can provide dynamic information which is highly valuable for driver assistance systems.

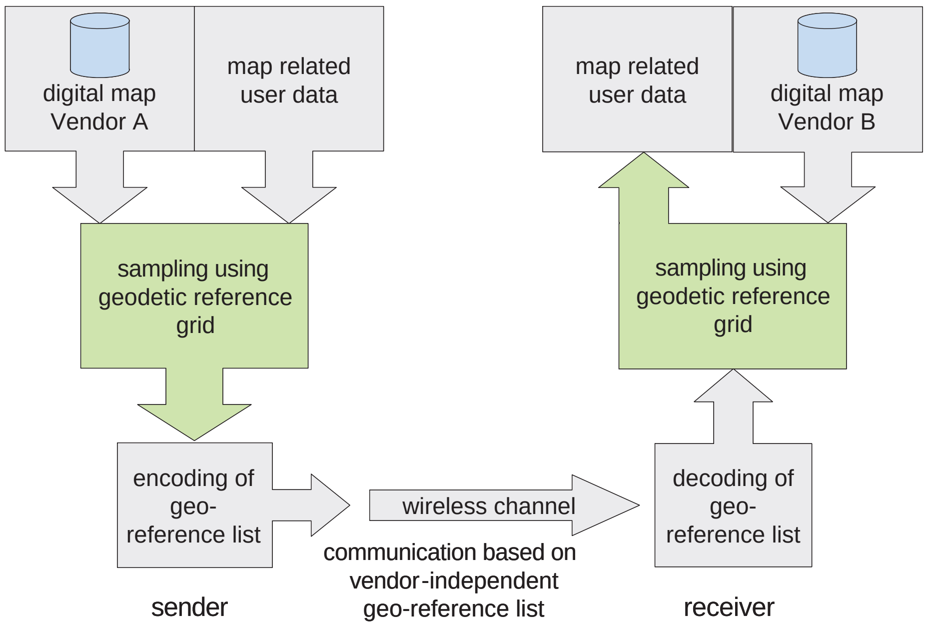


Figure 7.9: Vendor-independent communication of map based user data.

Furthermore, in contrast to the basic SODAD method introduced in the previous chapter, it allows interaction of low-end systems without pre-installed maps with systems which use a conventional vector map. Similarly, it enables the exchange of map based status information in a vendor-independent way, as shown in Figure 7.9. Before transmitting status information via IVC, all vehicles convert the data to a vendor-independent GRL. The receiver decodes the information by matching the GRL to its locally used vector map (similarly to the decoding process in TPEG).

7.4 Summary of Chapter

This chapter has demonstrated that the SODAD technique introduced in Chapter 6 can also be applied if no pre-installed digital map is available or maps of different vendors are used. Based on vehicular ad hoc communication and a satellite based positioning system, a self-generated road status map is obtained for the local area of a vehicle. This self-generated map allows a detailed status analysis and prediction of course and conditions ahead. It is valuable for driver assistance systems as well as for improving data dissemination in a VANET. However, for some applications – such as navigation – pre-installed digital vector maps are still required. In this case, self-generated status maps can complement the pre-installed vector map with dynamic status information.

VIII

Utility-Fair Broadcast (UFB)

The previous chapters have shown the advantages of broadcast based, store-and-forward methods in VANETs and have demonstrated techniques, which allow to achieve a large information range even if only a low number of all vehicles is equipped with an ad hoc communication system. An important technical challenge that has not been considered in-depth so far is the question of controlling the load on the wireless channel. The well-known end-to-end congestion control and bandwidth sharing approaches, e.g. as used in TCP, cannot be used in the highly dynamic VANETs where broadcast communication is dominating. This is due to the fact that in these networks usually a bidirectional end-to-end link between source and sink of the information is not available. Therefore, congestion control needs to be implemented in a decentralized and self-organizing way within the VANET without relying on feedback of the receiver(s).

A simple heuristic solution for reducing the required data rate has already been considered in Section 6.4 with the *Provoked Broadcast* technique. It achieves a good performance, reduces the required data rate and can react to overload conditions. However, it does not consider fairness of the resulting bandwidth allocation. Furthermore, since the scheme is part of the VANET application itself, it can only effectively avoid overload conditions if either only this single application is active at a vehicle or the scheme is implemented (in an identical way) within each VANET application.

In contrast, in future VANETs many different applications will be active – with completely different bandwidth, priority and delay requirements. Therefore, the question of congestion control on the wireless medium is reconsidered in a systematic way in this chapter. A general method for congestion control is derived that can be implemented in a decentralized and self-organized way, locally in each VANET node. The scheme provides a fair allocation of bandwidth within the local area, across multiple applications and multiple nodes. It is applicable for broadcast as well as unicast data and can easily be implemented on top of a CSMA MAC layer. Detailed network simulations show that such a fair and controlled allocation leads to a significant performance improvement of the VANET, in particular if a larger number of vehicles is equipped with the ad hoc communication system.

The second half of the chapter presents extensions which allow an implementation within the network layer. Thus, individual VANET applications do not need to implement their own congestion control scheme, but instead can rely on the lower layers – much like it is done in conventional networking applications. A suitable communication architecture is introduced and evaluated by simulations considering the influence of the type and number of simultaneously active VANET applications.

8.1 Motivation and Challenges

Efficient utilization of available resources and the avoidance of overload conditions are of high importance for any communication network. For a CSMA based VANET – as assumed in this thesis – the wireless bandwidth is shared among all nodes within carrier-sense range and needs to be distributed in a fair and optimal manner.

Because of the specific properties of a VANET, this task is particularly challenging:

- The network itself and the bandwidth available for a node are highly dynamic.
- Many VANET applications are based on geocast/broadcast, which implies that end-to-end schemes are hard to apply.
- The priority of a data packet changes dynamically, depending on the local situation. Since it may be influenced by recent transmissions of others (as in the Provoked Broadcast scheme, Section 6.4), by the type of applications active at other nodes in the local area, by the type of data and the current load, the priority is not a static value and can hardly be anticipated at the sender.
- The VANET has no central control instance, which could provide admission control or optimal bandwidth allocation. The control scheme has to be implemented in a completely self-organized way.

Thus, in a VANET based on broadcast communication, congestion control is a highly important topic [WR05a, WR05b]: Without proper congestion control, bandwidth might be consumed by low priority applications, leading to starvation of more important applications.

8.1.1 Problem Example

It is well-known that the Carrier-Sense Multiple Access (CSMA) approach of the IEEE 802.11 protocols can lead to severely unfair conditions in larger wireless ad hoc networks [XS01]. If communication occurs mainly in form of end-to-end data flows, this unfairness can partly be mitigated by the RTS/CTS protocol in combination with per-flow fair scheduling [LMCL01]. These per-flow mechanisms cannot be applied in VANETs, since in this case broadcast communication is dominating.

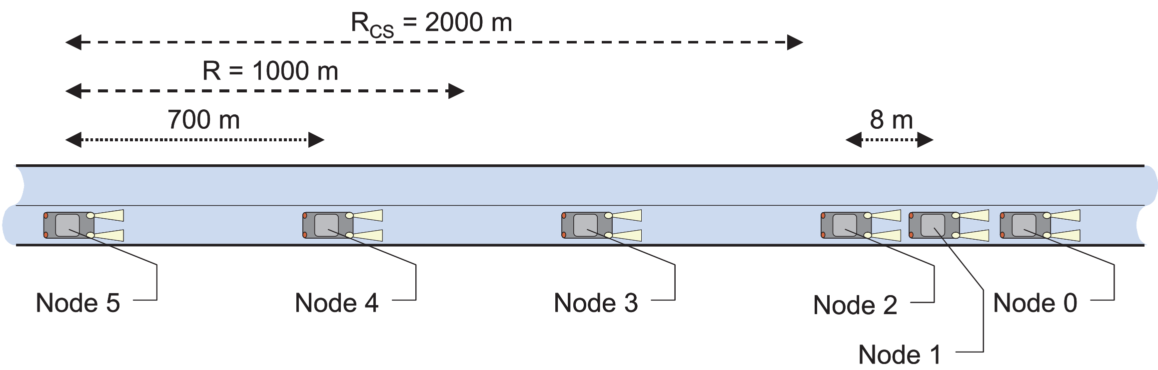


Figure 8.1: Simple deterministic street scenario (transmission range $R = 1000\,\text{m}$).

A typical example for the resulting fairness problem is illustrated in Figure 8.1, where a group of three closely located vehicles (Nodes 0-2) is followed by three other vehicles with a mutual distance of 700 m. It is assumed that all nodes constantly have broadcast packets to transmit (are continuously backlogged). The deterministic two-ray ground propagation model is used with a transmission range R set to 1000 m, carrier sense range R_{CS} is 2000 m. There is a known tradeoff between spacial reuse and interference when determining the carrier sense range. It can be shown that a ratio of 2–3 of carrier sense range R_{CS} to transmission range R is optimal [YV05]. Most approaches in literature assume $R_{CS} = 2 \cdot R$, which is also the case here.

Table 8.1: Transmitted data rates in the deterministic example scenario (without UFB).

	No. 5	No. 4	No. 3	No. 2	No. 1	No. 0
Rate [kb/s]	937	1	2	337	339	339

The results listed in Table 8.1 demonstrate the unfair situation resulting from a purely CSMA based approach: Nodes 0 to 2 share the full available bandwidth by sending at about 338 kb/s each. Node 5 – being at a distance of more than the carrier-sense range to the group of nodes Nodes 0 to 2 – also completely saturates the wireless medium by sending 937 kb/s.

This leads to the starvation of Nodes 3 and 4, which are only able to transmit 1-2 kb/s. The reason for this unfair distribution of available bandwidth is that Nodes 3 and 4 need to compete with two adjacent groups inside their carrier sense range, which are not aware of each other. Therefore, most of the time Node 3 and Node 4 sense a busy medium due to an ongoing transmission of Node 5 and/or one node in the group of Nodes 0 to 2. In contrast, Node 5 does not sense the carrier of Nodes 0 to 2 (and vice-versa). It assumes that the medium is idle and continuously transmits.

Furthermore, the data rates, which are available for the individual nodes, depend solely on their position and local environment – the *utility of the transmitted data for the local network* does not have any influence. For example, although Node 3 might have data to transmit that is of high importance (i.e. high utility) for the other nodes in the local neighborhood, it could be starved by Nodes 0-2.

For these reasons, in this chapter a completely different approach is advocated which is based on a utility-based congestion control scheme [WR05a] implemented at each node in the VANET: By a decentralized algorithm, each node is assigned an individual data rate corresponding to the utility of its packets for the network. This implies that a vehicle sensing or forwarding information of high utility for other vehicles in the local area is allowed to transmit at a high data rate.

Due to the high mobility and the resulting rapidly changing topology, reducing the data rate during congestion cannot be solely done at the data source. Broadcasted and forwarded packets leading to congestion in one part of the network may be successfully received in a less congested part. Therefore, most nodes will constantly need to drop a fraction of the data packets and the aim of the proposed scheme is to drop exactly those packets which have the lowest utility for the local context.

The proposed self-organizing approach, called Utility-Fair Broadcast (UFB), can significantly improve the performance of VANET applications by avoiding the starvation of individual nodes and favoring the transmission of packets with a high utility for the VANET. In addition, congestion control is achieved by selectively dropping data packets of low utility and thereby keeping the network load below a specified threshold. UFB is identically applied to uni- and broadcast data.

8.2 System Model

The system model assumed in this chapter is a generalization of the model introduced in Chapter 6:

- The VANET is formed of N individual vehicles equipped with a wireless air interface, a digital map and a GPS receiver.
- A VANET application, which is active at a vehicle, generates messages. These are disseminated to other vehicles via the VANET.
- A message consists of S individual information elements (with $S \geq 1$). For each information element, a unique ID and a time stamp is included.
- Applications transmit messages with the available information in broadcast packets. For simplicity, a one-to-one mapping of messages to packets is used.
- The received information values are stored on-board the vehicle within the application and continuously updated. If a newer information element for a specific ID (i.e. element with same ID but higher time stamp) is received, it replaces the previously stored one.
- No routing or location service is used. Forwarding of information over multiple hops is solely achieved by the combination of broadcast transmissions with a store-and-forward approach, as in SODAD.

For segment-oriented applications such as those introduced in Chapter 6, the information elements of a message are the data values for individual road segments.

However, the model also allows the transmission of arbitrary data values not related to a specific road segment.

Before transmission, data packets are stored in a packet queue at the network layer. For each enqueued data packet p, the node can calculate a utility value $u_a(p) \in [0, 1]$ corresponding to the utility of transmitting the data packet at the current point in time. The function $u_a(p)$ is provided by the application a and encoded in the packet header. For example, in a traffic information system based on inter-vehicle communication, a data packet with new information on the traffic status would be assigned a higher utility value than a data packet with information already known in the local area. (Details on the encoding of the function $u_a(p)$ in the packet header are presented in Section 8.7.)

A CSMA based MAC is assumed: A node senses that the medium is busy in the carrier sense range R_{CS} and can receive data from nodes within the transmission range R. As in the previous problem example, it is assumed that $\frac{R_{CS}}{R} = 2$. For simplicity, link adaptation is not considered – all nodes constantly use the same PHYsical layer (PHY) mode for transmitting/receiving data.

8.3 Utility Concept for VANETs

The notion of utility in a VANET used in the following differs in various aspects from utility measures in related work (Sec. 8.9): A utility value is always calculated on a per-packet basis and the approach is therefore suitable for broadcast data. This form of utility function is unlike the utility concept assumed by most other utility-based scheduling algorithms: Instead of computing the utility as an application specific function of the available bandwidth [BCL98], in UFB the utility is a function of the data packet and the current environment. The reason for this more general utility concept is that in VANETs due to the high mobility and the dependency on the local context, the utility value can be completely different for two consecutive data packets.

More specifically, the utility $u_a(p)$ of a data packet p denotes the *estimated utility of transmitting packet p at the current point in time*. For a typical VANET application, this could correspond, e.g., to the number of updated information values divided by the total number of segments within the data packet. Furthermore, the utility $u_a(p)$ depends on the situation within the local area of a node and is continuously

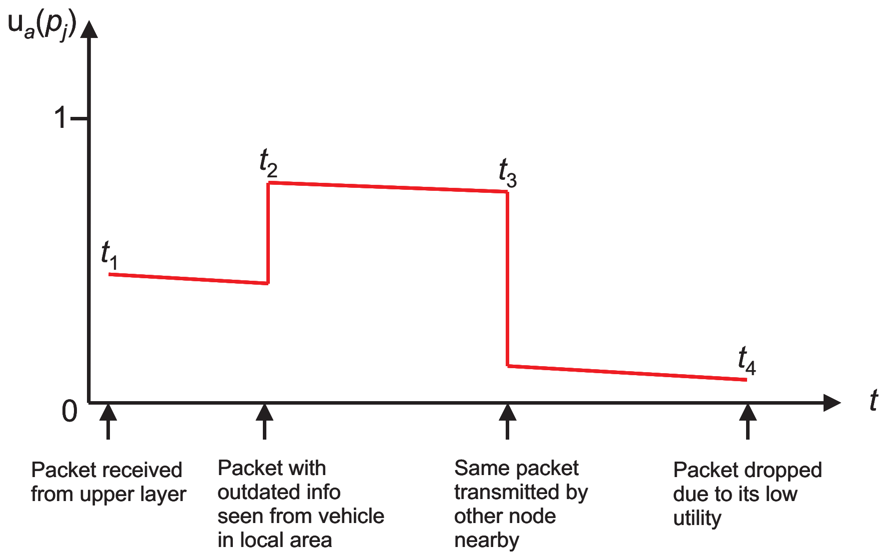


Figure 8.2: Example for packet utility $u_a(p_j)$ of a data packet p_j.

updated. This allows the system to adapt to the high rate of topological changes which is typical for VANETs. Since this adaptation is performed locally at each node, no explicit signalling between data source and receivers is required.

An example is shown in Figure 8.2, where the progression of the utility value $u_a(p_j)$ for a specific packet p_j is depicted over time. At time t_1, the packet is received from the upper layer (i.e. the application) and enqueued. Later, at a time t_2, a packet including outdated information for element IDs within p_j is observed by the node. This increases the utility value $u_a(p_j)$ since for the network it would be of high utility to inform the node sending the outdated information of the updated state included in p_j. (Similar to the reasons for causing a provocation in the heuristic Provoked Broadcast scheme in Section 6.4.) Analogously, when a packet containing information identical to p_j is received at time t_3, the utility decreases drastically. In between the events at time instants t_i, the utility function in the example decreases slightly due to the increasing age (and therefore decreasing accuracy) of the packet.

Since the utility function $u_a(p)$ can be arbitrarily defined by the respective applications (a typical example is given later in Section 8.5), the utility concept is more flexible than Provoked Broadcast. It also avoids disadvantages of the heuristic scheme – such as requiring an identical implementation within each application.

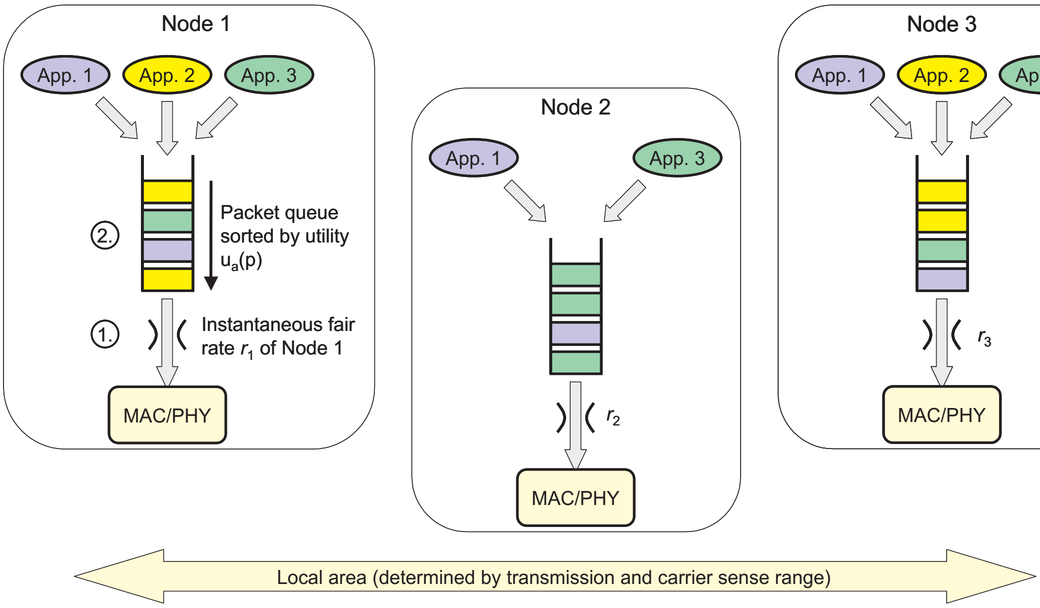


Figure 8.3: Schematic illustration of self-organized packet scheduling in local area.

8.4 Packet Scheduling Algorithm

The utility-based scheduling applied in UFB consists of two parts (Figure 8.3):

1. Each node i claims an utility-fair instantaneous transmit rate r_i which is determined by a decentralized scheme executed at each node.

2. A *highest utility first scheduling* performed locally at each node: Data packets stored within the local packet queue are transmitted in order of their utility $u_a(p)$. Whenever the node is allowed to transmit a data packet, the packet p which maximizes $u_a(p)$ is dequeued from the local queue and transmitted.

While the latter part can easily be implemented based on the utility functions $u_a(p)$ encoded in the packet header (Sec. 8.2), the assignment of the instantaneous fair rate requires coordination with all nodes within the local area.

8.4.1 Objective for Rate Assignment

Due to the CSMA mechanism, a node shares the available transmission bandwidth with all nodes within a distance of R_{CS}. The basic idea of UFB is that, instead of assigning $\frac{1}{N}$th of the available bandwidth[1] to each node, it is much more efficient to assign data rates based on the (average) utility of data packets transmitted by a node. Thereby, nodes transmitting information with a high utility for the VANET will be allowed to consume a larger share of the available bandwidth than nodes with less important information.

This process is particularly challenging, since the *effective data rate* can be significantly lower than the *raw data rate* of the air interface. The reason is that during periods of time in which the node detects power above the carrier-sense threshold but is unable to successfully decode the received data, it will defer from own transmissions. The effective data rate is the average rate at which the node was able to send or receive data in the recent past. It is time variant since it depends on the local environment of the node and needs to be estimated continuously. (A possible implementation of this estimation of the effective data rate is outlined later in Section 8.4.4.) While the effective data rate is influenced by transmitted and received data, a node can locally only adjust the rate of transmission.

In UFB, the objective for transmit rate assignment is as follows. Let η_i denote the utility per byte of the packet $p_{i,k}$ (created by application a) that has the maximum ratio of utility to packet size $s_{i,k}$ at a node i. If K packets are stored in the packet queue of the respective node i, the value of η_i is calculated as

$$\eta_i = \max_{k=1...K} \left(\frac{u_a(p_{i,k})}{s_{i,k}} \right) \tag{8-1}$$

Assume that N_i^{2hop} nodes are within a distance R_{CS} of node i. In UFB, the objective is to assign a transmit rate r_i to node i which is proportional to η_i and fulfills the fairness constraint

$$\frac{r_i}{\eta_i} = const., \quad \forall i \in [1, N_i^{\text{2hop}}] \tag{8-2}$$

while maximizing the total rate $\sum_i r_i$.

8.4.2 Determining the Instantaneous Transmit Rate

In order to determine the instantaneous transmit rate r_i for node i, a locally common value β_i^{local} of the ratio of effective data rate to utility has to be achieved. Due to the

[1] Note that due to the known fairness problems of the IEEE 802.11 protocol [XS01], even the assignment of $\frac{1}{N}$th of the available bandwidth would not be trivial.

assumption that $\frac{R_{CS}}{R} \approx 2$, β_i^{local} is calculated for a two-hop range by the following algorithm: Each node has an estimate $\hat{\mu}_\eta$ of the expected value of η calculated over all packets transmitted in the local area. (Details on the estimation procedure are given later in Section 8.4.3.)

For each node i, β_i denotes the available effective data rate per node per utility calculated as

$$\beta_i = \frac{\hat{B}_i^{\text{eff}}}{\hat{N}_i^{\text{1hop}} \hat{\mu}_\eta} \tag{8-3}$$

where $\hat{N}_i^{\text{1hop}}$ is the observed number of nodes in transmission range and $\hat{B}_i^{\text{eff}}$ is the observed effective data rate in the recent past.

Every data packet transmitted by a node i includes β_i and its 1-hop minimum β_i^{1hop}. The β_i^{local} at a respective node i is therefore calculated as the minimal β_i of all nodes in carrier sense range (i.e. 2-hop range from node i) based on the received and own β_i^{1hop} values.

$$\begin{aligned} \beta_i^{\text{local}} &= \min_{m=1\ldots\hat{N}_i^{\text{2hop}}} (\beta_m) \\ &= \min_{j=1\ldots\hat{N}_i^{\text{1hop}}} \left(\beta_j^{\text{1hop}}\right) \end{aligned} \tag{8-4}$$

Node i claims the temporary fair rate r_i for its data packet p by Eqn. 8-5, where $\theta \in (0, 1]$ denotes a system specific factor characterizing the target load for the system.

$$r_i = \eta_i \cdot \theta \cdot \beta_i^{\text{local}} \tag{8-5}$$

By inserting Eqn. 8-3 and 8-4 while assuming an unbiased estimation of $\hat{\mu}_\eta$, this can be rewritten as

$$r_i = \frac{\theta \cdot \eta_i}{E\{\eta\}} \cdot \min_{j=1\ldots\hat{N}_i^{\text{2hop}}} \left(\frac{\hat{B}_j^{\text{eff}}}{\hat{N}_j^{\text{1hop}}}\right) \tag{8-6}$$

In other words, the node claims a share r_i of the available bandwidth per node that is proportional to the utility of its own transmission compared to the average utility of data transmissions. The packet is handed to the MAC with a delay of $\frac{s_{i,k}}{r_i}$. This fulfills the fairness constraint in Eqn. 8-2, since $\theta \cdot \beta_i^{\text{local}}$ is constant within carrier-sense range of a node i.

8.4.3 Average Utility in Local Area

For obtaining its local value β_i in Eqn. 8-3, a node requires an estimate $\hat{\mu}_\eta$ of the expected value of the utility per byte η for its local neighborhood. For simplicity, a recursive estimation procedure

$$\hat{\mu}_\eta(n) = \alpha^k \cdot \hat{\mu}_\eta(n-1) + (1-\alpha^k) \cdot \eta \tag{8-7}$$

is proposed, which updates the estimated value $\hat{\mu}_\eta$ whenever a new data packet p_j with η utility per byte is received or sent at a node. Here, $\hat{\mu}_\eta(n-1)$ and $\hat{\mu}_\eta(n)$ denote the estimated value before and after the update, respectively. The constant $\alpha \in [0,1]$ determines the influence of the previously estimated value.

The exponent k (for the sake of brevity, the indices i and j are omitted) takes the packet size s_j and the currently seen effective data rate $\hat{B}_i^{\text{eff}}$ at node i into account. This is necessary to achieve an approximately constant adaptation speed independent of the size of data packets and the locally seen effective data rate.

$$k = \frac{s_j}{s_{\max}} \cdot \frac{B_{\max}}{\hat{B}_i^{\text{eff}}} \tag{8-8}$$

$s_{\max}$ is a constant for the maximum packet size, $B_{\max}$ is the maximum effective data rate of the considered system (i.e. raw data rate of the air interface).

8.4.4 Monitoring the Effective Data Rate

In order to determine the effective data rate which is currently available at a node, a simple monitoring concept is implemented on top of the MAC layer (Figure 8.4). At constant time intervals of T_{mon}, the times T_i during which the MAC was transmitting, receiving or sensing a busy medium are determined. Furthermore, the number of bytes s_i^{tx} and s_i^{rx} successfully transmitted and received during each interval T_i is recorded. The estimated effective data rate in period T_{mon} is

$$\hat{B}_{\text{eff}} = \frac{\sum_{i=1}^{K} s_i^{\text{tx}} + s_i^{\text{rx}}}{\sum_{i=1}^{K} T_i}, \qquad K \in \mathbb{N} \tag{8-9}$$

8.4.5 Target Load

The target load $\theta \in [0,1]$ in Eqn. 8-5 determines the average load for which the system schedules packet transmissions. Under the assumption that a node has

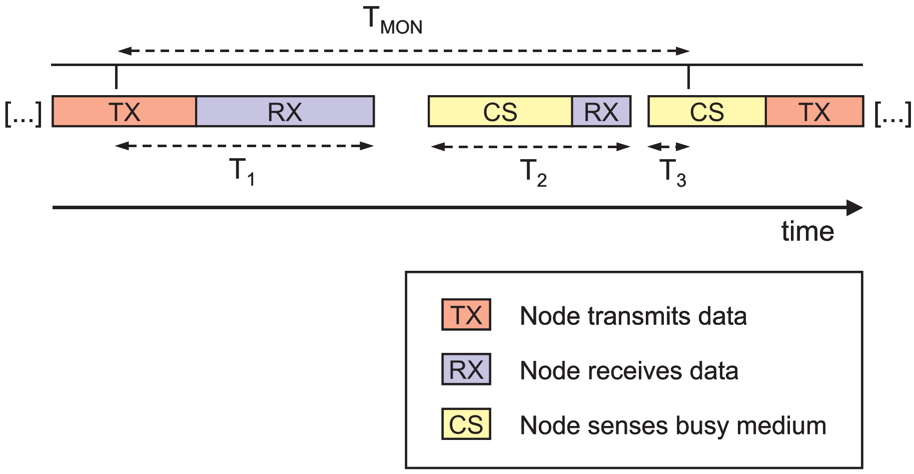


Figure 8.4: Illustration of monitoring the effective data rate in the period T_{mon}.

obtained a value of β_i^{local} which is the minimum of the available effective data rate within carrier-sense range, the scheduler performs a fair allocation of bandwidth to the individual nodes. The calculation of β_i^{local} relies on a simple signalling scheme where a node includes the values of β_i and its 1-hop minimum β_i^{1hop} in each transmitted data packet (see Section 8.4.2 for details).

However in the considered system, it can occur that two groups of vehicles are separated by a distance $d \in (R, R_{\mathrm{CS}}]$. This leads to the situation that the two groups influence each other but are not able to communicate (i.e. signal their local β_i values). If no intermediate data exchange is performed between these two groups (e.g. by vehicles on the opposite lane) for a long time, the values of β_i^{local} in the two groups can start to diverge. In the worst case, this will lead to a situation where one group uses the complete available bandwidth and the other group is starved.

An example for this critical situation is shown in Figure 8.5, where the group of Node 0 and 1 is separated by more than the transmission range R from Nodes 2 and 3. However, both groups are within carrier-sense range R_{CS} of each other and thus mutually influence each other significantly. Choosing a constant target load θ in this case can lead to diverging values for the effective data rate per utility β_i^{local} in such a situation. Figure 8.6(a) shows an example, in which after about 500 s the values in the two groups start to diverge. This leads to an unfair distribution of the bandwidth since the assumption of a common value of β_i^{local} is violated.

This divergence is avoided by varying the target load depending on the currently

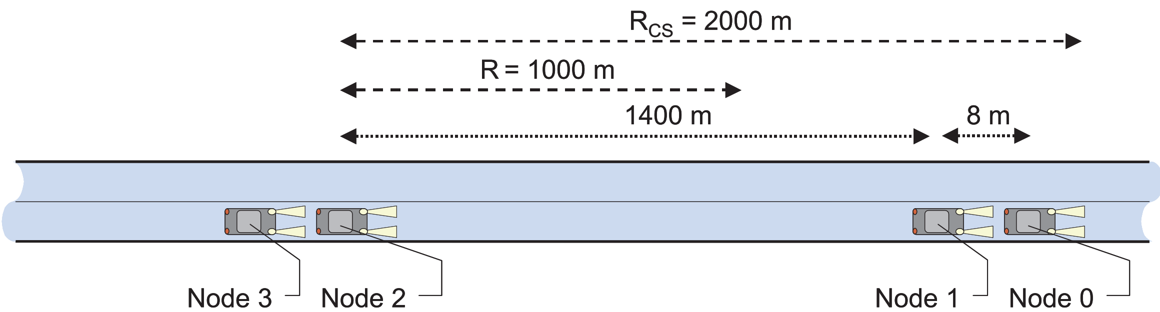
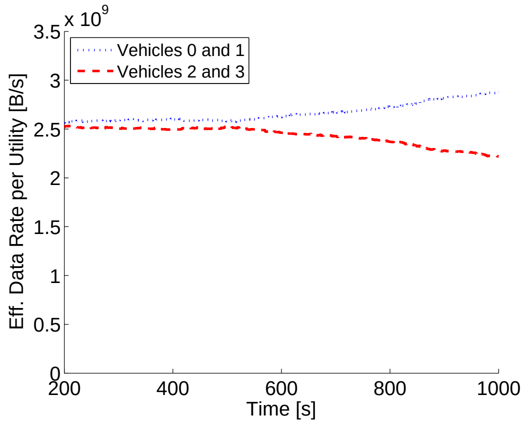
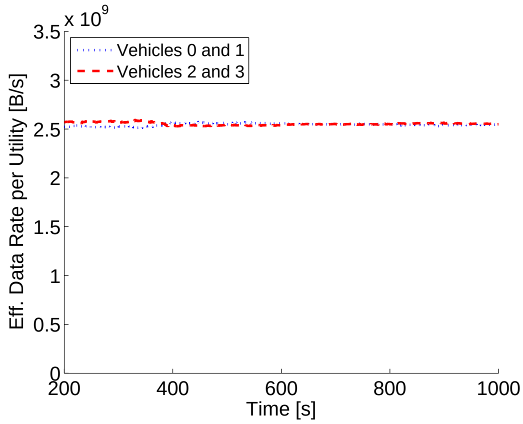


Figure 8.5: Simple example scenario illustrating the divergence of β_i^{local} in non-communicating vehicle groups.



(a) Constant target load θ.



(b) Adaptive target load $\theta(\hat{B}_i^{\mathrm{eff}})$

Figure 8.6: Locally available effective data rates in critical scenario of Figure 8.1. Diverging values of effective data rate per utility β_i^{local} are avoided if the target load is adapted depending on $\hat{B}_i^{\mathrm{eff}}$.

measured effective data rate $\hat{B}_i^{\text{eff}}$ in an interval $[\theta_{\text{min}}, \theta_{\text{max}}]$. For simplicity, in the following it is assumed that $\theta(\hat{B}_i^{\text{eff}})$ decreases linearly with increasing ratio of $\hat{B}_i^{\text{eff}}$ to B_{max} according to

$$\theta(\hat{B}_i^{\text{eff}}) = \theta_{\text{min}} + (\theta_{\text{max}} - \theta_{\text{min}}) \cdot \left(1 - \frac{\hat{B}_i^{\text{eff}}}{B_{\text{max}}}\right) \tag{8-10}$$

This modification achieves a convergence of the values of β_i^{local} for both groups (Figure 8.6(b)) even if the groups are not within transmission range. The reason is that as soon as β_i^{local} in one group is significantly lower than in the other, the group with a higher β_i^{local} (and a thus a higher $\hat{B}_i^{\text{eff}}$) schedules for a lower target load which counteracts the divergence.

8.5 *Simulative Performance Analysis*

For performance evaluation, UFB is implemented within the *ns-2* based VANET simulator known from the previous chapters. Based on network simulations, the performance of a VANET using UFB is compared with a reference system without an UFB scheduling layer in a stochastic highway scenario.

8.5.1 Simulation Environment

For each node, a complete network protocol stack consisting of a) the application (conforming to the model described in Section 8.2), b) User Datagram Protocol (UDP), c) Internet Protocol (IP), and d) IEEE 802.11 MAC/PHY is simulated.

The proposed UFB mechanism is integrated in the simulated node as outlined in the previous section. The ns-2 packet format is extended to include a short UFB header consisting of the three information values required for UFB scheduling (i.e. β^{local}, β^{1hop} and η).

Two different scenarios are considered:

- a simple deterministic scenario without mobility and
- a stochastic scenario with road traffic mobility

The parameters for communication and traffic simulation are identical to those introduced for Scenario B (Tables 6.3 and 6.4) with the following modifications: Load control and fair scheduling schemes such as UFB are mainly important in situations with a high density of vehicles equipped with the ad hoc communication system. Therefore, it is important to consider high IVC penetration values γ. However, the complexity and resulting computation time of the simulation increases strongly with increasing γ.

In order to be able to evaluate UFB with reasonable effort, the complexity of the simulated scenario was decreased by reducing the length of the highway to 40 km and by assuming a lower MAC layer data rate of 0.1 Mbit/s for the stochastic scenario. This has the additional effect that the chance of a congested medium is increased without the need to increase the data rate of the active IVC applications. An overview of the additional simulation parameters for UFB is given in Table 8.2.

Table 8.2: New and modified parameters in the stochastic scenario for UFB evaluation.

Parameter	**Value**
Constant α (recursive estimation of $\hat{\mu}_\eta$)	0.95
Target Load Interval $[\theta_{\text{low}}, \theta_{\text{high}}]$	[0.75, 0.95]
MAC data rate B_{max}	0.1 MBit/s
Max. length of utility-sorted packet queue	5 packets
Packet size $s_{i,k}$ (at network layer)	1072 Bytes
Total road length	40 km

In these first simulative evaluations, the focus is on a verification of the assumption that the self-organizing UFB technique can provide a fair allocation of the available data rate and control the load on the wireless medium. Per vehicle, exactly one VANET application is active. It uses the SODAD technique for disseminating information within a local area. More complex scenarios involving different types of data and multiple simultaneously active applications per node are presented in the simulative evaluation of application-independent UFB in the second half of this chapter.

8.5.2 Simulation Results

The main performance criteria calculated within the simulations are the achieved data rates, the number of packet collisions and the delay for the dissemination

Table 8.3: Transmitted data rates in the deterministic example (Figure 8.1) with utility-fair broadcast.

	No. 5	No. 4	No. 3	No. 2	No. 1	No. 0
Utility [u/pkt]	0.1	0.1	0.1	0.1	0.1	0.1
Rate [kb/s]	138	148	135	138	138	138

of new information within the VANET. Independent of a specific application, the deterministic scenario investigates if a utility-fair allocation of data rates is achieved.

For a specific application, such a utility-fair allocation should result in an improved performance (i.e. lower delay for information propagation) and reduction of the number of packet collisions. This is investigated in the stochastic scenario.

8.5.2.1 Simple Deterministic Scenario

Firstly, the deterministic example (Section 8.1.1, Figure 8.1) is revisited. As in Section 8.1.1, no mobility is present and the standard data rate of 1 Mbit/s is used for the IEEE 802.11 MAC. Packet queues of the nodes are continuously backlogged, i.e. each node continuously has data to transmit.

Table 8.3 shows the achieved data rates, if all applications at every node transmit data packets with a utility of $u_\mathrm{a}(p) = 0.1$ per packet. Compared to results for the reference system (Table 8.1), the starvation of nodes 3 and 4 is successfully avoided by UFB and all nodes transmit with approximately the same data rate. Since all nodes are sending data with identical utility value, this is the expected result for an utility-fair scheduling.

In order to further illustrate the utility-fairness, a second simulation is performed, in which the application at Node 3 is modified to send data packets with a constant utility of 0.3. As expected, in this case Node 3 can transmit about three times as much data as the other nodes (Table 8.4).

8.5.2.2 Stochastic Scenario

The second scenario presented is a stochastic scenario consisting of a 40 km highway section. The simulation parameters are identical to those in Table 8.2. At each

Table 8.4: Transmitted data rates with utility-fair broadcast and three times higher utility of data sent by Node 3.

	No. 5	No. 4	No. 3	No. 2	No. 1	No. 0
Util. [u/pkt]	0.1	0.1	0.3	0.1	0.1	0.1
Rate [kb/s]	82	82	233	78	78	78

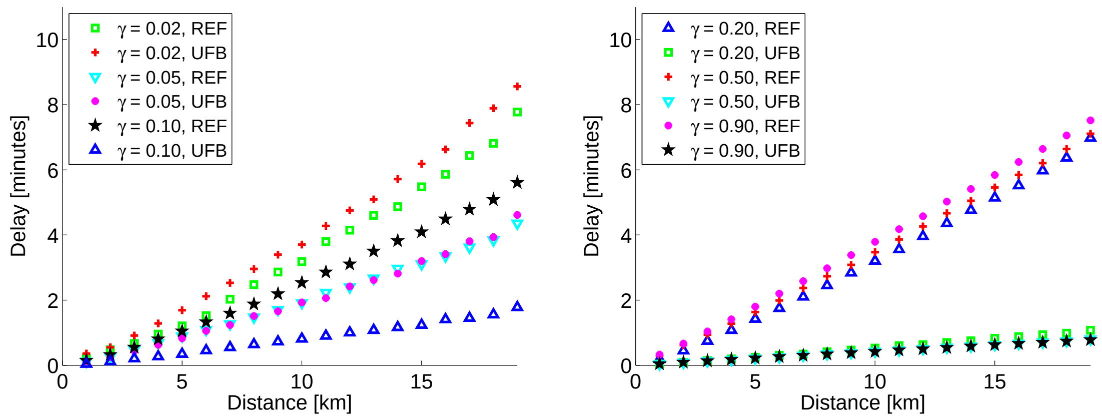
equipped vehicle, a typical VANET application using the SODAD approach for information dissemination is assumed. The road is divided into segments with a length of 200 m and for each segment one data value and one time stamp per direction is recorded. The VANET applications enqueues one data packet each 500 ms in the utility-sorted packet queue (Figure 8.3).

The utility function of a specific application is an important parameter within the UFB scheme. Motivated by the results for the heuristic Provoked Broadcast scheme in Section 6.4, the following utility function is chosen for the simulated VANET application. The utility $u_{\mathrm{a}}(p)$ of a data packet is determined by the number of new and different segment data values and the distance to the previous sender.

$$u_{\mathrm{a}}(p) = \frac{\left(N_p^{\mathrm{upd}} + q_p^{\mathrm{new}}\right) d_{\mathrm{tx}}}{(S+1)R} \tag{8-11}$$

The number of updated segments N_p^{upd} corresponds to the number of segments which have newer time-stamp and a different information value. Additionally, $q_p^{\mathrm{new}} \in [0,1]$ indicates the newness of the message, $d_{\mathrm{tx}} \in [0,R]$ is the distance to the node which transmitted last. S is the number of segments per packet and R the transmission range. With these assumptions, $u_{\mathrm{a}}(p)$ is always within the interval [0,1] and qualifies as an utility function.

Since UFB considers the packet content when calculating the utility of a data packet, the model for the application data values is also of importance. The data values of a road segment change randomly and independently – here a rate of one change per 600 s is assumed. The main performance criterion on the application level is the delay with which an updated value is received. It is calculated by the following procedure: Whenever an updated information value is received at a vehicle, it records the difference between the segment time stamp and the current simulation time.

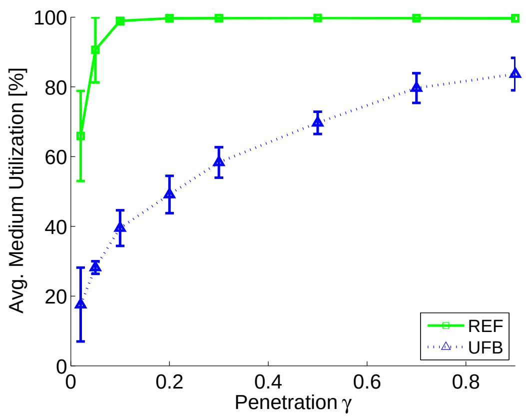


(a) Low penetration γ. (b) High penetration γ.

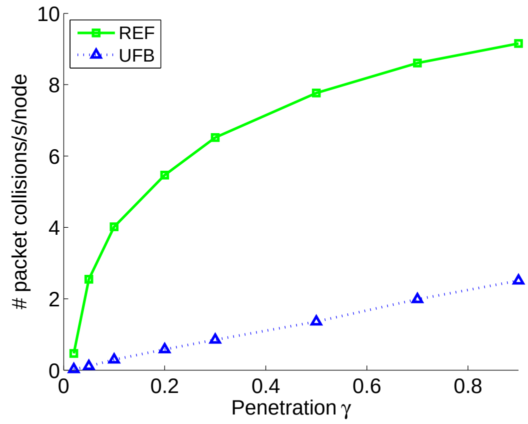
Figure 8.7: Delay for propagating new information in the stochastic scenario in a system with utility-fair scheduling (UFB) and a reference system (REF) without UFB.

Figure 8.7 compares the performance of the UFB-less reference system (REF) with the UFB based system (UFB). In case of low penetration (Figure 8.7(a)), the performance of both systems is similar. If only 2 % of all vehicles are equipped, the reference system even slightly outperforms the UFB system for larger distances. In situations with such a low penetration, congestion almost never occurs and therefore UFB cannot improve the performance. Since UFB limits the maximum data rate of an individual node to a fraction of the total data rate (determined by the UFB target load), the reference system can disseminate information faster in some situations. However, the achieved delay improvement compared to UFB in this case is only low compared to the absolute value.

With increasing penetration, the advantages of UFB become visible: At 5 % penetration, both systems perform equally well. With 10 % penetration, the delay of the UFB system is less than half of the delay of the reference system. As expected, this performance gain due to UFB even increases for higher penetration values shown in Figure 8.7(b). However, increasing the penetration γ from 0.2 to 0.9 results in only a small additional reduction of delay for UFB. As known from Chapter 5, in this case the VANET is highly connected – the speed of information dissemination is mainly determined by the data rate of the air interface. To achieve an even lower delay, the data rate would need to be increased above 0.1 Mbit/s. For the reference system, increasing the penetration even results in an increased delay.



(a) Medium utilization.



(b) Data packet collisions.

Figure 8.8: Medium utilization and packet collisions with and without UFB.

It can be suspected that the performance of UFB for penetration values of $\gamma > 0.1$ is superior because in this case much bandwidth is wasted in the reference system due to the transmission of data packets with low utility and data packet collisions. This assumption is confirmed by Figure 8.8. In 8.8(a), the average medium utilization visible at a node and the corresponding 99 % confidence intervals are shown. For the reference system, the medium is completely utilized even if only 10 % of all vehicles are equipped. In contrast, UFB controls the load and avoids congestion leading to a lower number of data packet collisions, as shown in Figure 8.8(b).

In order to illustrate the behavior of the UFB scheme, Figure 8.9 additionally depicts

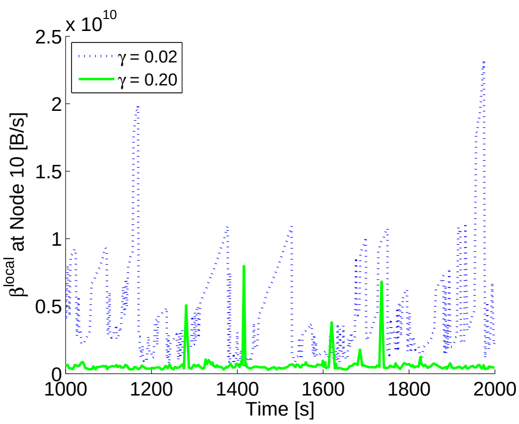


Figure 8.9: Example for the progression of β^{local} at a specific node.

an example for the progression of β^{local} at a specific node. For a very low penetration ($\gamma = 0.02$), the vehicle accumulates new information for several seconds while there is no other vehicle in range. This leads to periods with high values of β^{local} which end when the vehicle meets and informs another vehicle. In situations with high penetration ($\gamma = 0.20$), the vehicle can almost continuously inform other vehicles. Short peaks occur when a changed information value is propagated.

8.6 Optimality of UFB

It has already been established that UFB provides a fair allocation of the available bandwidth since it fulfills Equation 8-2. However, an open question until now is if the allocation of data rates r_i in UFB is also optimal in the sense that it maximizes the sum $\sum_i r_i$. This issue is considered in the following.

Besides the requirement of a fair allocation, an additional constraint for the considered system is that – on a long-term basis – the available effective bandwidth B_i^{eff} is not exceeded for any node i within carrier-sense range. (For simplicity, the target load θ is set to 1.0 and omitted here and in the following.)

$$E\left\{\sum_{k=1}^{N_i^{\text{1hop}}} r_k\right\} \leq B_i^{\text{eff}}, \quad \forall i \in \left[1, N_j^{\text{2hop}}\right] \tag{8-12}$$

Recall that the effective bandwidth B_i^{eff} is determined considering transmissions in 1-hop range only. Therefore, the sum of rates r_i is also within 1-hop range.

Corollary 1: Exactly one optimal fair assignment exists.

Since the ratio $\frac{r_i}{\eta_i}$ is constant, the rate assignment is completely determined by knowing a single rate r_i. The sum of all rates is a monotonically increasing function.

Corollary 2: In the optimal solution, B_i^{eff} is completely used for at least one node.

$$\exists i \in \left[1, N_j^{\text{2hop}}\right], \quad E\left\{\sum_{k=1}^{N_i^{\text{1hop}}} r_k\right\} = B_i^{\text{eff}} \tag{8-13}$$

Otherwise, a valid better solution could be achieved by multiplying all rates r_i with a constant $c > 0$ and the solution would not be optimal.

In UFB, each node i claims a data rate of $\eta_i \beta_i^{\text{local}}$ according to Eqn. 8-5 where β_i^{local} is the minimum effective data rate per utility per node within carrier-sense range. Let j denote the node, called *critical node* in the following, which determines β_i^{local}, i.e. $\beta_i^{\text{local}} = \beta_j$.

Considering the situation at the critical node j, the following equations hold:

$$\begin{aligned} E\left\{\sum_{i=1}^{N_j^{\text{1hop}}} r_i\right\} &= E\left\{\sum_{i=1}^{N_j^{\text{1hop}}} \eta_i \beta_i^{\text{local}}\right\} \\ &= E\left\{\sum_{i=1}^{N_j^{\text{1hop}}} \eta_i\right\} \cdot \min_{m=1\ldots\hat{N}_i^{\text{2hop}}} (\beta_m) \\ &= N_j^{\text{1hop}} \cdot E\{\eta_i\} \cdot \beta_j \\ &= N_j^{\text{1hop}} \cdot E\{\eta_i\} \cdot \frac{B_j^{\text{eff}}}{N_j^{\text{1hop}} \cdot E\{\eta_i\}} \\ &= B_j^{\text{eff}} \end{aligned} \tag{8-14}$$

Therefore, B_i^{eff} is completely used at the critical node j. With Corollary 2, it follows that this assignment of the values r_i is the optimal solution.

8.7 Application Independent UFB

An important aspect of UFB, which has not been considered so far, is where and how the technique should be implemented. Until now, it was implicitly assumed that any node can calculate the utility $u_{\text{a}}(p)$ of any data packet p of application a. However, since the utility can depend on the information content encoded within the packet and the local situation of a node, obtaining $u_{\text{a}}(p)$ is not trivial. It is particularly challenging, if a vehicle only forwards a data packet and does not run the application a that created the data packet.

A classic principle in the design of communication systems is the so called end-to-end argument [SRC84, CeS+98]: *Whenever possible, functionality should be implemented in the end systems (i.e. above the network layer) instead of being implemented on the lower layers of a communication system.* The reason is that the application is aware of its specific requirements and semantics – if the functionality is implemented at a lower layer, some applications might require a different kind of service or even be harmed by the implementation in the lower layer. Furthermore, hop-by-hop implementation of a service on a lower layer cannot guarantee the correct end-to-end availability of the service. The end-to-end argument is the main reason to advise against the use of a active networks[2] [CeS+98] and to shift as much functionality as possible to the end systems.

In principle, the implementation of schemes for improving the efficiency of data dissemination such as UFB is feasible at the end system. E.g., the Provoked Broadcast scheme presented in Chapter 6 is implemented at the application layer and leads to a significant performance improvement compared to a non-adaptive system. However, for UFB an implementation within each vehicle (i.e. not only the end systems) is necessary for the following reasons:

- In order to achieve the utility-fair assignment of data rates, UFB needs to be implemented at each hop since the data source cannot anticipate the highly dynamic network conditions in the VANET.
- For broadcast data transmission, the end points are not known at the time of transmission. Thus, an end-to-end approach is not feasible.
- In UFB, the data rate corresponding to a specific utility of a data packet depends on the local situation of a node, including the network load and the utility of data transmitted by other active applications. The information required for such a relative prioritization is not available within a single application.

Furthermore, especially for market introduction, it would also be favorable to be able to install a "basic module" [SMM+05] which can perform forwarding including UFB without running the application itself. The main idea is to use a standardized store-and-forward module integrated within each vehicle in addition to vendor specific applications.

For all these reasons, an application independent implementation of UFB in each vehicle is required. In this case, the main challenge for integrating UFB in currently existing systems is to allow an *application independent calculation of the packet utility*

[2] In an *active network*, the operation of the network can be dynamically influenced by packets, e.g. by including code to be executed within a data packet.

$u_{\mathrm{a}}(p)$ at each hop [WR05a]. In the following, first a suitable communication architecture is presented. It achieves an application independent UFB implementation and thus allows to use arbitrary combinations of applications at each node in the VANET. Afterwards, the system model used for the simulations is extended to accommodate different types of VANET applications, which can be simultaneously active at each node. The complete system is then evaluated by detailed network simulations.

8.7.1 Communication Architecture

Per hop functionality for data dissemination (i.e. routing in classical networks) is implemented within the network layer of a communication system [Tan88]. As a consequence, an implementation of UFB as extension of the network layer is assumed in the following, as illustrated in Figure 8.10. This extension is also referred to as the *UFB scheduler*, since it enforces the utility-fair scheduling of transmissions.

In order to allow calculation of the utility $u_{\mathrm{a}}(p)$ at the network layer independently of the application, the following components are introduced:

1. **Descriptor:** Describes the packet content in an application independent way.
2. **Environment Variable:** Provides information on the local situation and state of a node.
3. **Utility Function:** A (mathematical) function allowing the calculation of the utility of a data packet based on descriptors and environment variables.
4. **Update Function:** Updates the environment variables whenever a packet is received or transmitted.

They are used in a simple cross layer approach: For each data packet generated at the application layer, a small UFB header (Figure 8.11) is added consisting of two application specific binary encoded functions: the *utility function* and the *update function*. Both are composed of *descriptors*, *environment variables* and mathematical operators. By applying the utility and the update function in the packet header, the application specific utility of a data packet can be calculated at the network layer at any point in time, even if the respective application is not active at an individual

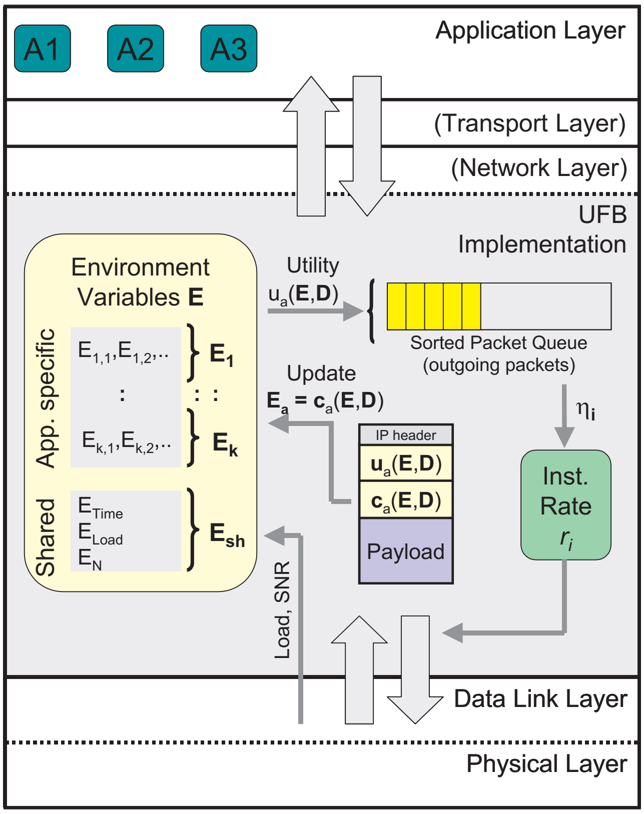


Figure 8.10: Overview of the UFB implementation in a node.

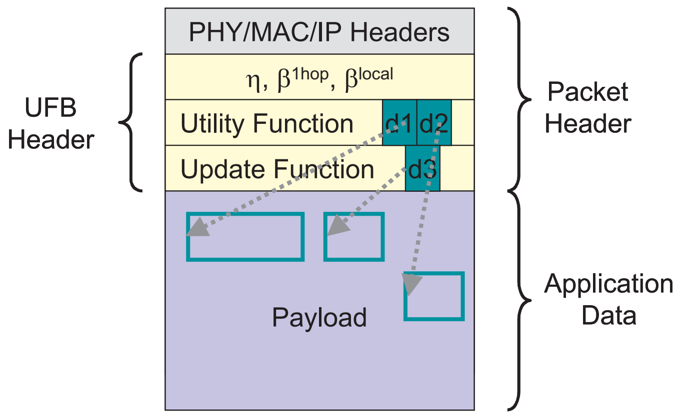


Figure 8.11: Packet structure including the UFB header.

node that is forwarding the data packet. In the following, these two functions and their components illustrated in Figure 8.10 will be described in more detail.

8.7.1.1 Descriptors

A *descriptor* is an abstract description of the data in the data packet. It is either a single data value directly inserted in the UFB header or a reference (i.e. pointer) to a data section within the payload. A single UFB header can contain multiple descriptors. For simplicity, the n descriptors in the kth packet received from application a will be denoted by $\mathbf{D}_{a,k}$ with

$$\mathbf{D}_{a,k} = \{d_1, d_2, \ldots, d_n\} \tag{8-15}$$

A typical example for a descriptor in a VANET application and its usage in a utility function is presented later during the performance analysis (Section 8.8).

8.7.1.2 Environment Variables

For calculating the utility of a data packet, the UFB scheduler requires state information on the current local context of the vehicle. This information is stored in form of *environment variables* which are regularly updated by applying an update function (see Section 8.7.1.4). The current implementation supports the four data types for environment variables listed in Table 8.5.

Table 8.5: Supported data types for environment variables and descriptors.

Type	**Dimensions**
single (floating point) number	
bit field	1- or 2-dimensional
byte field	1- or 2-dimensional
floating point field	1- or 2-dimensional

Two classes of environment variables exist in UFB:

- **Application Specific Environment Variables ($\mathbf{E}_a$)** are created and updated by an individual application a. The meaning of an application specific environment variable is known only within the respective application that created the environment variable. It characterizes the data currently disseminated by an application. For example, an application disseminating short messages in a specific area could use an unique message identifier as an application specific environment variable.

- **Shared Environment Variables ($\mathbf{E}_{sh}$)** are created and updated by the UFB scheduler itself and can be read by all applications. The current implementation supports the following shared environment variables:
  - time,
  - position,
  - number of nodes in single hop communication range,
  - local network load,
  - average signal to noise ratio.

8.7.1.3 Utility Function

The *utility function* $u_a(p_k)$ is used to determine the utility $U_{a,k}$ of transmitting a data packet p_k of application a at the current point in time. This information is required for the fair rate assignment as introduced in Section 8.4.1. The utility $U_{a,k}$ depends on the shared environment variables $\mathbf{E}_{sh}$, the application specific environment variables $\mathbf{E}_a$ and the descriptors $\mathbf{D}_{a,k}$ encoded in the header of the data packet.

$$U_{a,k} = u_a(p_k) = u_a\left(\mathbf{E}_{sh}, \mathbf{E}_a, \mathbf{D}_{a,k}\right) \quad U_{a,k} \in [0,1] \tag{8-16}$$

8.7.1.4 Update Function

Update functions are used to update the knowledge on the local area (i.e. environment variables) based on received and transmitted data packets. Upon reception/transmission of data packet p_k with descriptor $\mathbf{D}_{a,k}$, the new value of the environment variables $\mathbf{E}'_a$ is the result of the update function $\mathbf{c}_a(\cdot)$

$$\mathbf{E}'_a = \mathbf{c}_a\left(\mathbf{E}_{sh}, \mathbf{E}_a, \mathbf{D}_{a,k}\right) \tag{8-17}$$

where $\mathbf{E}_a$ and $\mathbf{E}'_a$ denote the set of environment variables before and after sending/receiving the data packet, respectively.

8.7.1.5 Function Encoding

For encoding the update and utility functions in the packet header, a simple Type-Length-Value (TLV) encoding is implemented. A small interpreter then reads and evaluates the utility and update function in the packet header. (For the sake of brevity, the detailed specification of the used format is omitted here. A typical utility function can be encoded in only 3-20 bytes.)

8.7.1.6 Packet Scheduling

The procedure for decentralized UFB packet scheduling at each node is described in pseudocode in Algorithm 2. It implements the UFB concept using the utility and update functions introduced in Sections 8.7.1.3 and 8.7.1.4.
The UFB scheduler becomes active if one of the following four events occurs:

a) a new packet is enqueued,

b) the scheduler's *send timer* expires,

c) the lower layer (MAC/PHY) indicates that it is able to send the next data packet ('resume') or

d) the lower layer indicates the reception of a data packet.

Whenever a new data packet $p_{a,k}$ is handed down by application a on the node, its utility per byte $\eta_{a,k} = \frac{u_a(p_{a,k})}{s_{p_{a,k}}}$ is calculated and the packet is enqueued in the utility sorted packet queue. Based on the instantaneous fair rate r_i, an instantaneous delay d_i for the head of line packet is calculated at the node. Using the procedure outlined in Algorithm 2, the packet p_{a_0,k_0} with the maximum utility per byte is afterwards scheduled for transmission.

Algorithm 2: Basic implementation of UFB algorithm (pseudocode)

$blocked \leftarrow false$, $t_{TX} \leftarrow now$;
while *1* **do**
  update $\mathbf{E}_{sh}$;
  if *upper layer has packet* **then**
    insert packet in utility-sorted queue, new head-of-line packet is p_{a_0,k_0};
    if *blocked* **then**
      continue ;
    $d_i \leftarrow \frac{s_{a_0,k_0}}{r_i}$;
    if *no send timer pending* **then**
      $t_{TX} \leftarrow now$;
    set send timer to expire at $t_{TX} + d_i$;
  if *send timer expired* **then**
    $t_{TX} \leftarrow now$;
    update $\hat{\mu}_\eta$, $\mathbf{E}'_a$;
    `Send(`p_{a_0,k_0}`);`
  if *lower layer finished sending* **then**
    if *utility-sorted queue empty* **then**
      $blocked \leftarrow false$;
      continue ;
    $d_i \leftarrow \frac{s_{a_0,k_0}}{r_i}$;
    if $now - t_{TX} \geq d_i$ **then**
      $t_{TX} \leftarrow t_{TX} + d_i$;
      `Send(`p_{a_0,k_0}`);`
    else
      $blocked \leftarrow false$;
      set send timer to expire at $t_{TX} + d_i$;
  if *lower layer has packet* **then**
    update $\hat{\mu}_\eta$, $\mathbf{E}'_a$;
    if *packets in queue and not blocked* **then**
      $d_i \leftarrow \frac{s_{a_0,k_0}}{r_i}$;
      set send timer to expire at $t_{TX} + d_i$;

8.7.2 Extended System Model

The system model known from Section 8.2 is extended to allow the investigation of heterogeneous VANET scenarios with different types of applications. This is feasible since the application independent calculation of the utility function now enables a forwarding node to evaluate the utility of a data packet even if it does not run an application of the type where the packet belongs to.

In detail, the following extensions of the model are introduced:

- Per vehicle, zero, one or multiple applications can be active.
- Applications are assumed to be independent of each other. Therefore, data values sensed by different applications are uncorrelated. For simplicity, all applications make use of the identical digital map and use the same road segment size.
- Applications can be of different types, e.g. distribute different kinds of data such as traffic information, weather information or hazard warnings. Different application types are modeled by assuming a different rate $1/T_{\mathrm{Ichange}}$ of changes for the segment information values.

In such a heterogeneous VANET where different vehicles use different sets of applications, it can occur that a node receives a broadcast/geocast data packet which cannot be associated with any locally active application. In this case, two options exist: The vehicle can simply ignore (i.e. drop) the respective data packet or it can perform some kind of multi-hop forwarding (flooding) procedure.

While the first option is simple to implement and can guarantee that data which no vehicle is interested in is successfully suppressed, it also means that market penetration needs to be achieved for each type of application individually. An application can only benefit of communication partners that execute the same application.

In contrast, the second option allows to deploy individual proprietary applications in addition to standardized common VANET applications. These manufacturer-specific applications rely on a standardized forwarding module in vehicles of other manufacturers for data dissemination. Therefore, the system model is extended with the concept of a basic Store-aNd-Forward (SNF) module which can optionally be active at a vehicle. A vehicle using the SNF module processes data packets according to the following model:

1. If a data packet is received that is associated with an active application at the node, it is delivered to the application. (In this case, the application is responsible for dissemination of data over multiple hops, as it is done by the SODAD applications.)
2. Otherwise, the packet is handed to the SNF module.
   (a) The SNF module has up to M different per-application queues, each holding up to L packets.
   (b) If a queue for the respective application already exists, the packet is enqueued. In case the maximum queue length L is exceeded, the oldest packet is dropped from the queue.
   (c) Otherwise, a new queue is created. It replaces the last recently used queue, if the maximum number of queues M is already reached.
   (d) The SNF module forwards data packets from the per-application queues in a round-robin fashion with a fixed rate. The forwarded packets are processed by the utility-fair scheduler in the same way as locally created packets.

The components of a node in this extended model are illustrated in Figure 8.12.

8.8 Performance Analysis of Application Independent UFB

The performance of the application independent UFB scheme is investigated under three different aspects. In the first simulation scenario, the influence of the number of simultaneously active applications per node on the system performance is evaluated. With increasing number of active applications, the network load and the chance for congestion increases. The results therefore also provide insight if UFB can achieve a better scalability of the VANET.

The second scenario considers different types of VANET applications. In this case, UFB can provide an application specific prioritization of data packets. The scenario

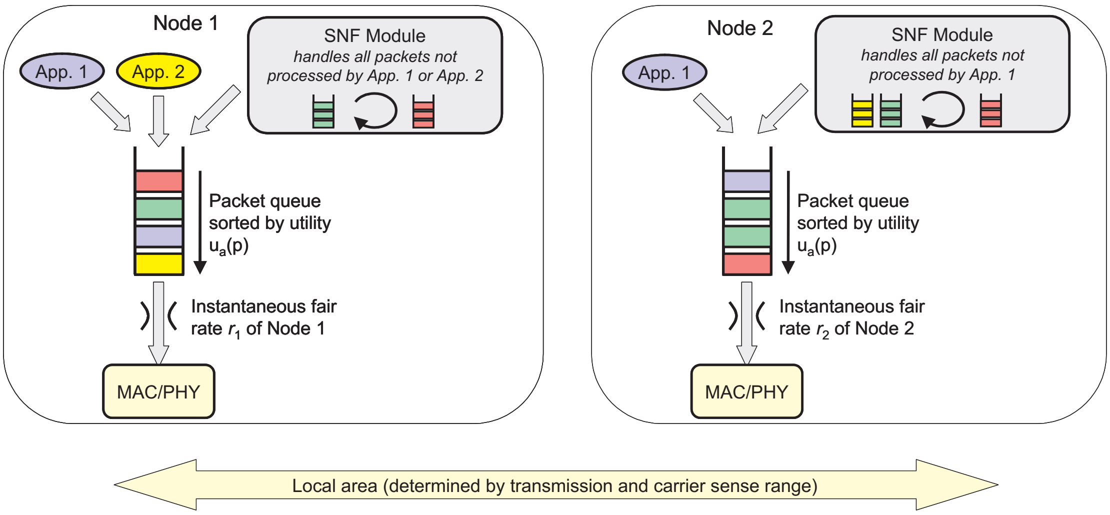


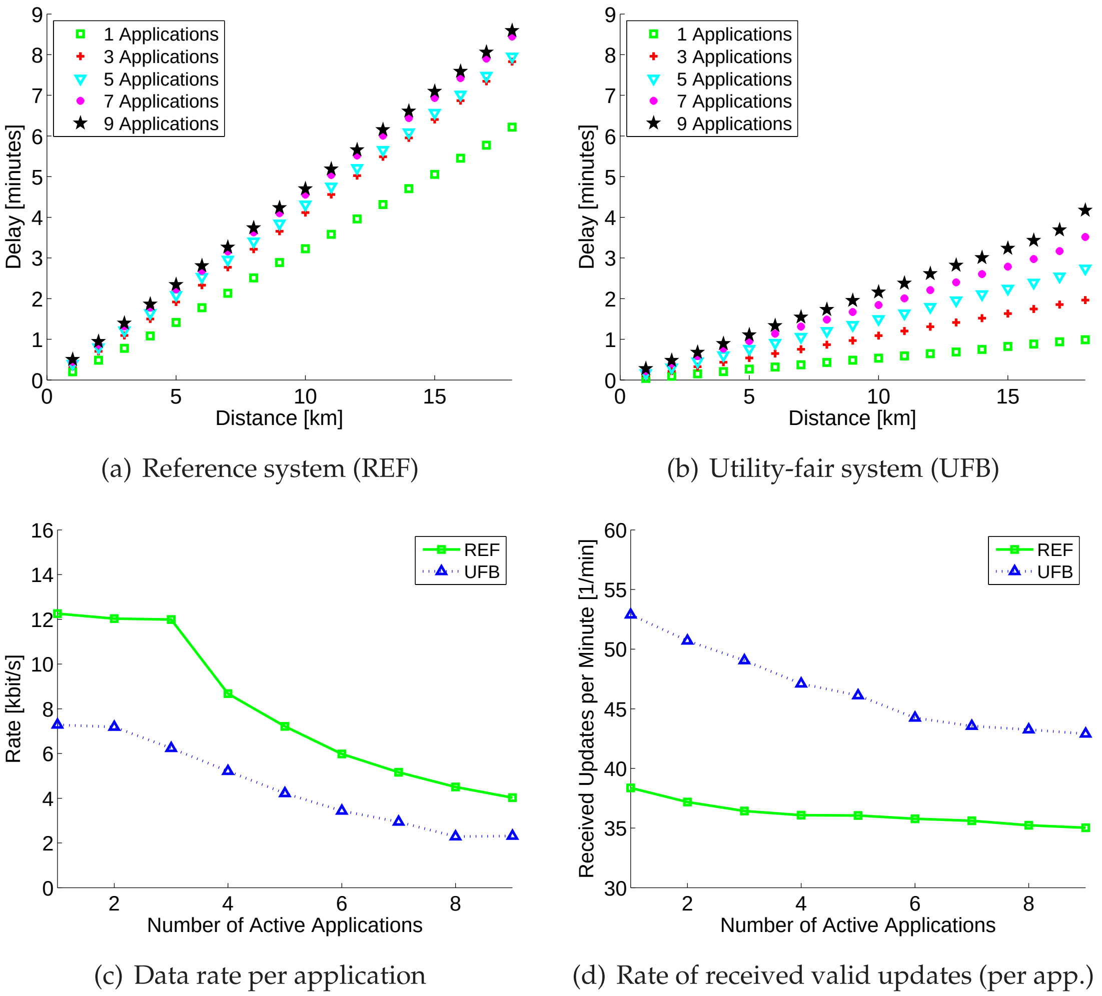
Figure 8.12: Illustration of extended system model with store-and-forward module.

investigates the impact of the application type on the achieved information propagation. Finally, the third scenario focusses on the influence of the basic SNF module. All scenarios use the same parameters as in the first part of the simulative evaluation of UFB (Scenario B, Tables 6.3 and 6.4, with the UFB parameters of Table 8.2). If not noted otherwise, the simulations also use an identical utility function and VANET application model, i.e. the per-segment values change randomly and independently with a period of $T_{\text{change}} = 600\,\text{s}$. Each application generates data at a constant rate of two data packets per second. The packet size $s_{i,k}$ at the application and network layer is 1072 Bytes. (It is assumed that even if fragmentation occurs on lower layers, e.g. due to requirements of the physical layer, packets are either completely received or dropped.)

8.8.1 Number of Simultaneously Active Applications

The application independent UFB implementation allows a coordinated congestion control across multiple applications. Therefore, in the first evaluated scenario, the number of simultaneously active applications per VANET node is increased while leaving the other parameters (in particular, the MAC data rate of $B_{\max} = 0.1\,\text{Mbit/s}$ and the VANET penetration $\gamma = 0.2$) constant.

In Figure 8.13, the performance of a system using the utility-fair broadcast scheme



(a) Reference system (REF)

(b) Utility-fair system (UFB)

(c) Data rate per application

(d) Rate of received valid updates (per app.)

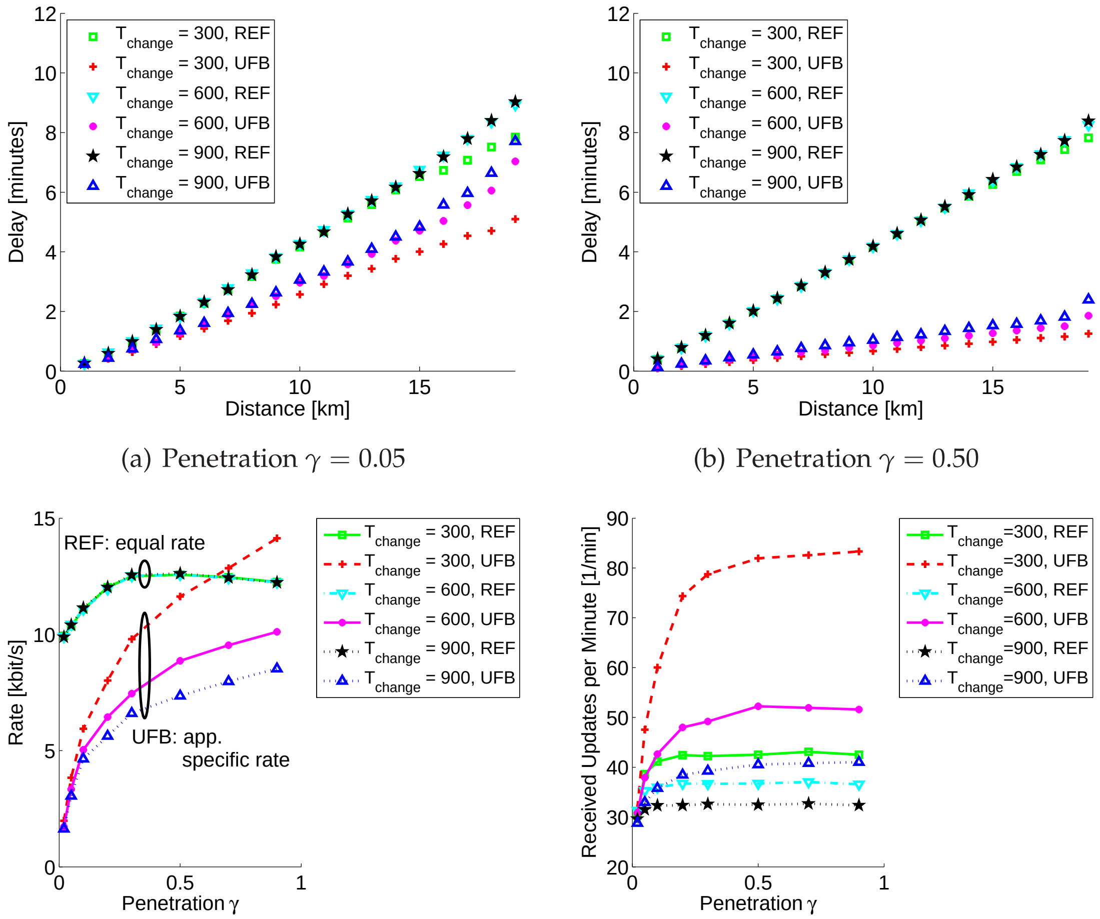
Figure 8.13: Influence of the number of simultaneously active applications on the system performance ($\gamma = 0.2$, MAC data rate $B_{\max} = 0.1\,\mathrm{Mbit/s}$, $T_{\mathrm{change}} = 600\,\mathrm{s}$).

is compared with an identical reference system without UFB. For both systems, the average delay with which information is distributed increases with the number of simultaneously active applications (Figures 8.13(a) and 8.13(b)). This is explained by the fact that with increasing number of applications, the available average (received) data rate per application decreases, as illustrated in Figure 8.13(c). However, the performance of the UFB system in terms of average delay for information propagation exceeds that of the reference system in all cases. For example, even with nine simultaneously active applications per node, the UFB system achieves a lower delay than the reference system. Additionally, the total number of received valid updates is higher (Figure 8.13(d)) although a lower data rate per application is used, i.e. a higher data rate does not necessarily lead to a better data dissemination.

8.8.2 Influence of Application Type

In order to study the influence of the application type, the previous scenario is modified to constantly use three simultaneously active applications per equipped vehicle. Applications of different types are simulated by varying the parameter T_{change}. An application disseminating more volatile information has a lower value for T_{change} than an application considering information with a longer period of validity. Here, values of 300, 600 and 900 s are used for T_{change} of applications 1 to 3, respectively.

The simulation results presented in Figure 8.14 show that the utility-fair scheduling results in different delays for the application types: Data packets of the application with a low value of T_{change} are disseminated with a lower delay than packets of applications with high T_{change} values. Since the applied utility function takes the number of new information elements per data packet into account (Equation 8-11), an application with a low value of T_{change} has a higher chance for data packets with multiple new information elements. Therefore, the system schedules a higher data rate for the application disseminating the more volatile information. In contrast, the reference system does not consider the utility of disseminated data which results in equal data rates for all application types (Figure 8.14(c)). The UFB system also achieves a higher rate of received valid updates as illustrated in Figure 8.14(d) since data packets with updated information elements have a higher priority.



(a) Penetration $\gamma = 0.05$

(b) Penetration $\gamma = 0.50$

(c) Data rate per application

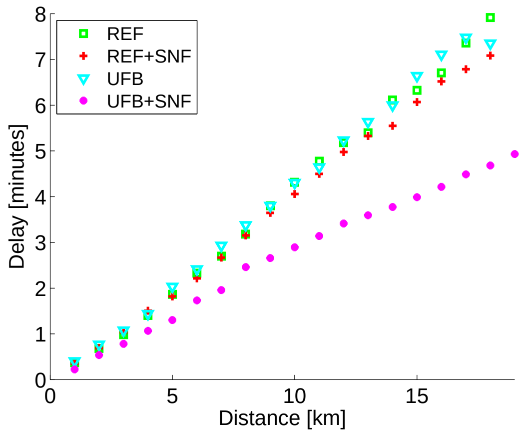
(d) Rate of received valid updates (per app.)

Figure 8.14: Influence of application type on the utility-fair system (UFB) and a reference system (REF) for different penetration values ($B_{\max} = 0.1\,\text{Mbit/s}$).

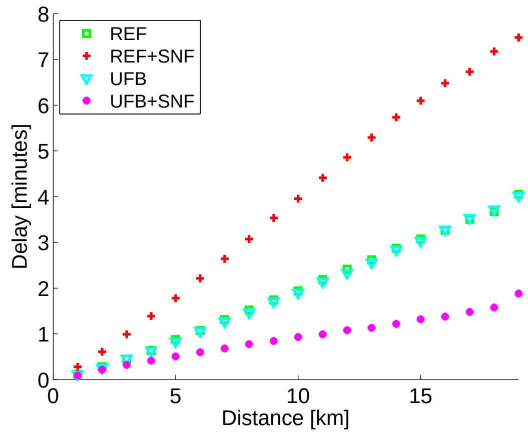
8.8.3 Impact of Basic SNF Module

An important aspect of the application independent UFB scheme is that it allows the implementation of congestion control for a Store-aNd-Forward (SNF) module, e.g. as specified in the extended system model of Section 8.7.2. The SNF module forwards data packets received at a VANET node if a suitable target application is not active. In this way, an application can benefit from equipped vehicles in transmission range, even if they do not run the respective application which generated the data packet.

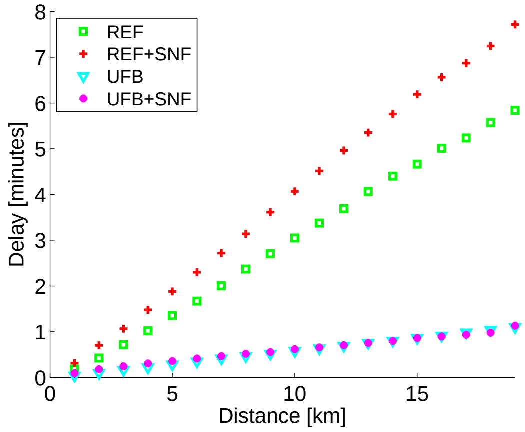
In the simulated scenario, only 25 % of the VANET vehicles use the evaluated



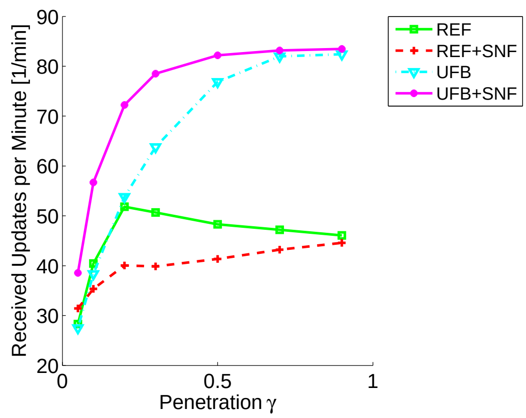
(a) VANET penetration $\gamma = 0.05$



(b) VANET Penetration $\gamma = 0.20$



(c) VANET Penetration $\gamma = 0.70$



(d) Rate of received valid updates

Figure 8.15: Influence of using a Store-aNd-Forward (SNF) module for the utility-fair (UFB) and reference (REF) system. In these scenarios, only 25 % of the VANET vehicles use the evaluated application (i.e. application penetration is $\frac{\gamma}{4}$).

application while the penetration γ varies. In this case, two kinds of penetration need to be distinguished: The term *VANET penetration* refers to the ratio of vehicle equipped with the ad hoc communication system, whereas the term *application penetration* considers only vehicles which participate in the VANET and run the evaluated application. In this scenario, the application penetration is $\frac{\gamma}{4}$.

Four different types of systems are evaluated:

1. reference system without store-and-forward module (REF),
2. reference system with store-and-forward module (REF+SNF),
3. utility-fair broadcast system without store-and-forward module (UFB),
4. utility-fair broadcast system with store-and-forward module (UFB+SNF).

For systems that use a SNF module, the forwarding rate for SNF is set to 50 % of the MAC data rate, i.e. 0.05 Mbit/s. The maximum number L of packets in the per-application queues of the SNF module is $L = 5$.

The plots in Figure 8.15 compare the performance of the four different system types for various VANET penetrations. For a low penetration of $\gamma = 0.05$, UFB+SNF outperforms the other tree systems (Figure 8.15(a)). In this case, only $\gamma/4 = 1.25\%$ of all vehicles use the considered VANET application. Since congestion is not likely, UFB without SNF does not improve the performance.

In Figure 8.15(b), $\gamma/4 = 5\%$ of all vehicles use the application itself. In this case, SNF and REF alone achieve an identical delay. Applying the store-and-forward module without UFB decreases the performance drastically, while UFB+SNF leads to a much better performance. This behavior can be explained by the fact that without UFB, a store-and-forward module can flood the network with redundant or outdated data. For a scenario with a very high penetration (Figure 8.15(c)), UFB and UFB+SNF achieve equal performance. In this case, even without the SNF module the chance of having a communication partner using the same application in range is high. Therefore, using a SNF module does not increase the performance.

Besides the delay, applying UFB+SNF also increases the rate of received updates, in particular for medium penetration scenarios where $\gamma \in [0.05, 0.50]$, i.e. the application penetration is in the range from 1% to 12%. Figure 8.16 summarizes the influence of the SNF module.

	UFB	REF
SNF	++	– –
no SNF	+	–

Figure 8.16: Overview of performance of utility-fair (UFB) and reference system (REF) with and without a store-and-forward (SNF) module.

8.9 Related Work

The UFB concept proposed in this chapter consists of two parts: the utility-fair scheduling and an application independent implementation of utility-based store-and-forward. In this section, an overview of related work for these two areas is given.

FAIR SCHEDULING AND CONGESTION CONTROL — Due to the wide use of the IEEE 802.11 protocols in ad hoc networks [XS01], there has been large interest in improving its fairness in multi-hop scenarios. A common approach is to use decentralized fair queueing algorithms [LMCL01], which can guarantee a fair rate for each individual data flow.

The notion of optimization based on utility is originally a micro-economic concept, applied to wireless networking first in [Lee95]. It has been used by several authors for centralized (wireless) scheduling, e.g. [GNB01, BCL98]. The general approach is to assume a strictly concave utility function $u(r)$ of the transmit rate r available for an individual data flow. It indicates the value of benefit achieved if a node transmits data at rate r. The individual data rates are then assigned in a way that the total utility of the system is maximized [GNB01, RB04].

However, these two approaches cannot be applied in the VANET scenario considered in this thesis. As mentioned in Section 3.3, communication in VANETs will mainly be broadcast-oriented, therefore, individual data flows, which can be assigned specific data rates, do not exist. In contrast to [GNB01], the utility functions $u(p)$ used in UFB are thus not a function of the data rate r but of an individual data packet p.

Specialized broadcast protocols for (multi-hop) data dissemination in vehicular ad hoc networks are proposed, e.g. in [Mic01, KEOO04] and with the Provoked

Broadcast scheme in Section 6.4. These protocols increase the efficiency of data dissemination by various strategies: [Mic01] uses a layered data structure where information irrelevant at larger distances from the source is discarded during the forwarding process. In [KEOO04], a Request to Broadcast (RTB)/Clear to Broadcast (CTB) handshake is used in order to select the furthest node for data forwarding. A similar effect is achieved by the Provoked Broadcast scheme, which adapts the inter-transmission interval (at the application layer) considering the nodes distance to the information source and the packet content. While the protocols presented in [Mic01, KEOO04, WER$^+$03a] could also be used in addition to UFB to facilitate a more efficient dissemination process, none of the existing approaches guarantees a (utility-)fair allocation of bandwidth for the individual nodes in a VANET.

While the UFB scheme aims at controlling the congestion within the VANET by adapting the rate at which each individual node transmits data, a different approach has been considered in [TMSH05] where power control for VANET safety applications is investigated. The authors argue that for safety applications the reception of regular update packets[3] with a specific minimal frequency is required in order to guarantee safety. Therefore, in cases of congestion, for safety applications it can make more sense to reduce the transmit power in order to control the congestion instead of sending too few update packets. While this approach is very attractive for delay-sensitive safety applications, [TMSH05] presents a centralized power control algorithm which is hard to apply in the decentralized VANET scenario. Furthermore, the focus in this thesis is on comfort applications, where in general the delay requirements are less stringent and the desired information range is relatively large.

Another multicast information dissemination scheme for wireless mobile ad hoc networks called Variable-Resolution Information Dissemination (VRID) is presented in [GGHL05]. It uses a *visibility function* that specifies the percentage of packets that reach a destination at a given distance. This is achieved by letting each data source select a distance according to a specific distribution up to which the data packet will travel. Similar to UFB, the VRID scheme uses a utility function (in VRID a function of visibility and distance) to derive the optimal visibility function for an application. However, the VRID does not allow to take the local situation of a node into account and thus cannot actively avoid overload conditions. Further-

[3] e.g. position and heading updates

more, a verification of the VRID concept in a realistic mobile environment is missing [GGHL05]. A forwarding behaviour similar to VRID can also be implemented as a special case of the UFB scheme presented in this chapter – it corresponds to UFB with static utility values.

UFB IMPLEMENTATION — In the implementation of UFB, the utility functions $u(p)$ are actively interpreted at a forwarding node in order to estimate the utility of transmitting a data packet at a specific point in time. This execution of a function stored in the packet header is in some aspects similar to the active networks [CeS+98] concept. However, the utility and update functions of UFB have a very restricted functionality due to the fact that their sole purpose is the calculation of a utility in the interval [0,1]. Thereby, most difficulties and security issues of the much more general active networks concept are avoided.

The communication architecture for VANETs developed in this chapter reconsiders several aspects of the traditional ISO/OSI architecture, e.g. end-to-end congestion control, per-packet and in-network processing. Similar requirements for a VANET protocol stack are reported in [FTMT+05, RRR05]. The system proposed in [RRR05] also includes stationary basic modules deposited at the roadside, so-called Message Relay Boxes (MRB). A MRB is compatible with the vehicular communication system, stores messages from passing vehicles and rebroadcasts. Additionally, messages are processed and compressed to more complex messages. Therefore, the functionality of an MRB is in parts similar to that of the SNF forwarding concept in this chapter. However, neither an evaluation of the MRB concept by simulation/experimental implementation nor a detailed description of the realization is currently available, and thus an in-depth comparison of the concepts is not possible.

8.10 Summary of Chapter

A decentralized and self-organized approach for congestion control in VANETs – the Utility Fair Broadcast (UFB) scheme – has been derived and evaluated in this chapter. The main idea for UFB is that each node claims a fair share of the locally available bandwidth. The rate available for each node is proportional to the utility of its data for the network and recalculated on a per-packet basis. In this way, UFB can react instantly to the rapidly changing topology in a VANET.

Furthermore, a communication architecture allowing the implementation of UFB in an application independent manner has been presented. Detailed VANET simulations show that UFB can significantly improve the performance of a VANET in terms of delay for information propagation and successfully avoids congestion even in cases of high penetration. The application independent UFB also enables the implementation of a store-and-forward module which continuously rebroadcasts received data packets if the specific target application of a data packet is not active at a node. The approach can utilize all equipped vehicles for disseminating information, even if the application is only installed at a fraction of the vehicles. This is particularly attractive for deploying additional vendor-specific VANET applications.

IX

Experimental Implementation

The positive results of the simulative performance evaluation of the proposed techniques for information dissemination and fair load control lead to the question if an implementation on currently existing off-the-shelf hardware is feasible. A related research question is the integration within existing standardized network protocols, e.g. to allow the communication with existing systems and facilitate a simple deployment.

This chapter presents the results of an experimental implementation of techniques investigated in the previous chapters: The self-organizing traffic information system is used as a typical application for the SODAD technique introduced in Chapter 6. It implements the heuristic Provoked Broadcast load control scheme. Furthermore, an integration of Utility-Fair Broadcast in the Internet Protocol Version 6 (IPv6) is outlined.

The prototype implementation serves several purposes. Experimental experience helps to determine the complexity of implementing the proposed schemes on existing hardware. The features of typical VANET applications and their benefit for the driver can be demonstrated in realistic driving situations. Additionally, the prototype implementation allows a validation of simulation results for small scenarios.

Test scenarios involving a larger number of experimental vehicles are very challenging with regard to hardware cost and vehicle coordination. Obtaining reproducible network conditions is almost infeasible. A possible alternative for tests and demonstrations involving a larger number of vehicles is testing the experimental system in a simulated environment, often referred to as *network emulation* [KMJ00]. A VANET emulator including support for the SOTIS application is presented in the last part of the chapter. It allows to demonstrate the interaction of experimental VANET applications with a large number of simulated nodes. The complexity of the emulation scenario is limited only by the available computational power – on standard PC hardware, scenarios with more than 35 nodes can be emulated.

9.1 Self-Organizing Traffic Information System Utilizing SODAD

In Section 6.1, the Self-Organizing Traffic Information System (SOTIS) was introduced as a typical example for a VANET application. It uses the SODAD technique for disseminating information on the traffic state (i.e., average velocity for each segment) within a local area of the vehicle. Very accurate traffic information is obtained for a local area of 50 to 100 km – even if only 1-3 % of all vehicles are equipped with VANET hardware. Since up-to-date traffic information is one of the most requested features of a navigation system, SOTIS is also used as example application in the experimental implementation.

9.1.1 Application of SODAD

For an experimental implementation of SOTIS, two functions need to be defined for SODAD (see Section 6.2): the aggregation function $a(\cdot)$ and the compression function $c(\cdot)$. The first defines how various data values sensed for a segment are aggregated, the second describes the integration of received data values.

For each road segment that a vehicle drives, it records the observed average velocity. The aggregation function $a(\cdot)$ is defined in a way that the data value $s_{n,i}$ for a segment i at node n is the arithmetic mean of own velocity d_1 and that of all K other vehicles in transmission range:

$$s_{n,i} = a(d_1, d_2, \ldots, d_{K+1}) = \frac{1}{K+1} \sum_{k=1}^{K+1} d_k, \quad K \in \mathbb{N} \cup 0 \tag{9-1}$$

The time stamp $t_{n,i}$ is set to the time of data aggregation. For node n, the tuple $(s_{n,i}, t_{n,i})$ sufficiently characterizes the current traffic situation in segment i, since the road type is also known.

Within the system, this per-segment information is distributed by single hop broadcast transmissions. Vehicles periodically transmit their locally available information and integrate received data values using the compression function $c(\cdot)$. For simplicity, the experimental system uses the compression function known from Equation 6-3: If information with a newer time-stamp is received for a segment, it replaces the previous outdated information for the same segment.

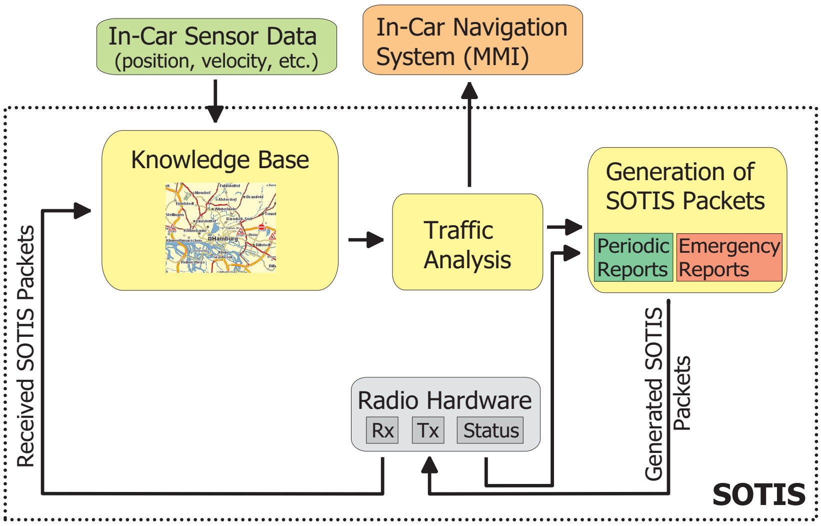


Figure 9.1: Functional structure of implemented SOTIS application.

Thus, each vehicle obtains traffic information for all road segments in the local area. This information can either be displayed to the driver (e.g. by coloring the roads displayed in the navigation system according to their traffic conditions) or it is used for calculating the best (i.e., fastest) traffic route for the current situation.

9.1.2 SOTIS System Structure and Components

Figure 9.1 illustrates the functional structure of SOTIS [WER^{+}05b]: Traffic information in form of tuples $(s_{n,k}, t_{n,k})$ is collected in the knowledge base. It contains traffic information for all segments within the local area (e.g. in a range of 200 km). Information is discarded if it has become outdated or the capacity of the knowledge base is reached. Using the information stored in the knowledge base, a traffic analysis is continuously calculated in each car. The analysis determines which information is to be included in the next broadcasted data packet. Data packets received from other vehicles are integrated in the own knowledge base by applying the compression function.

This functional structure is implemented by several independent modules which communicate using documented interfaces. This allows a flexible configuration of the prototype for different demonstration scenarios. Different types of sensors for sensing traffic information (e.g, CAN or GPS), multiple user interfaces for visualization and different mapping components (e.g. commercial or self-generated

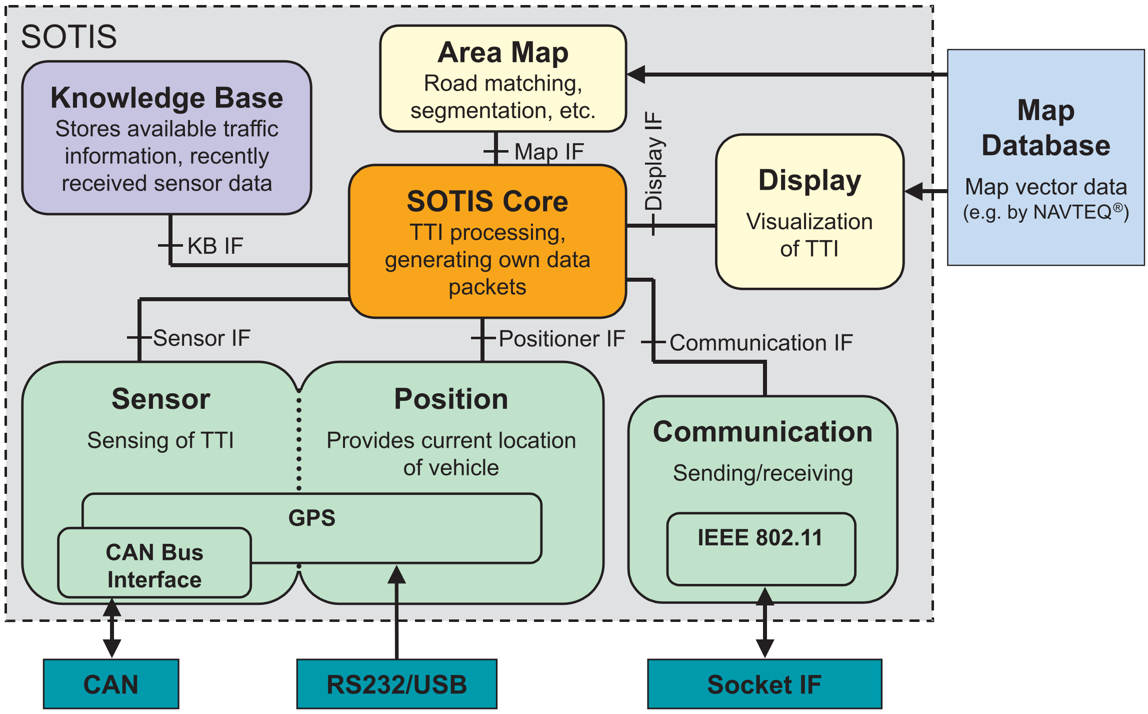


Figure 9.2: Block diagram of the SOTIS prototype.

maps) can be used. The application itself is platform independent – basically any system is suitable, where a Java virtual machine is available. In order to limit the costs and development effort, off-the-shelf hardware is utilized. However, this also means that the system cannot rely on features envisioned for future vehicular communication standards such as larger communication ranges.

The full functionality of the SOTIS application is realized by the 7 individual components [WER04] illustrated in Figure 9.2.

SOTIS CORE — The *SOTIS Core* coordinates the processing of traffic information and the composition of new data packets. Data is acquired using the three "lower" interfaces to the Sensor, Position and Communication components.

KNOWLEDGE BASE — The *Knowledge Base* stores the per-segment information available at each vehicle, indexed by the road identifier. It periodically evaluates the importance of each segment and discards information of low relevance, e.g. if the segment time stamp is outdated. The knowledge base also tracks the last time that a segment has been transmitted. In total, less than 20 bytes per segment are required.

AREA MAP — The main functions offered by the *Area Map* component are map matching and segmentation. Geographical coordinates can be converted to the triple (road identifier, segment number, direction) and vice versa. Map information can either be obtained from a commercial vector map[1] or a proprietary map format (combination of bitmap images and vector data).

DISPLAY — Visualization of the currently available information, the local area of the vehicle and all vehicles in direct communication range is performed by the *Display* component. Depending on the available information on the average velocity and the road type, traffic conditions are visualized by the color of a road segment: Red indicates very low, yellow medium and green high speeds (relative to speed limit for the respective road type). Figure 9.3 illustrates the implemented in-vehicle visualization and the additional components for evaluating and recording data.

POSITION — A *Position* component provides information on the current location of the vehicle – updated once per second – using a commercial GPS receiver connected via USB or RS232 interface. (In combination with map matching, GPS accuracy proved to be sufficient in the tests. It can be increased further by using on-board information such as steering angle or turning rate, which are available on the CAN bus.)

SENSOR — The *Sensor* determines the traffic information for the current location of the vehicle. For the prototype, information on the average velocity of a vehicle in a segment is used, obtained via GPS and/or CAN bus. CAN access (read access only) is either performed directly via a native interface or indirectly via a Vehicle API/Low Level CAN Framework layer [Vol, Lüb04].

[1]Currently, *NAVTEQ*® maps via *Mapsolute*® are supported.

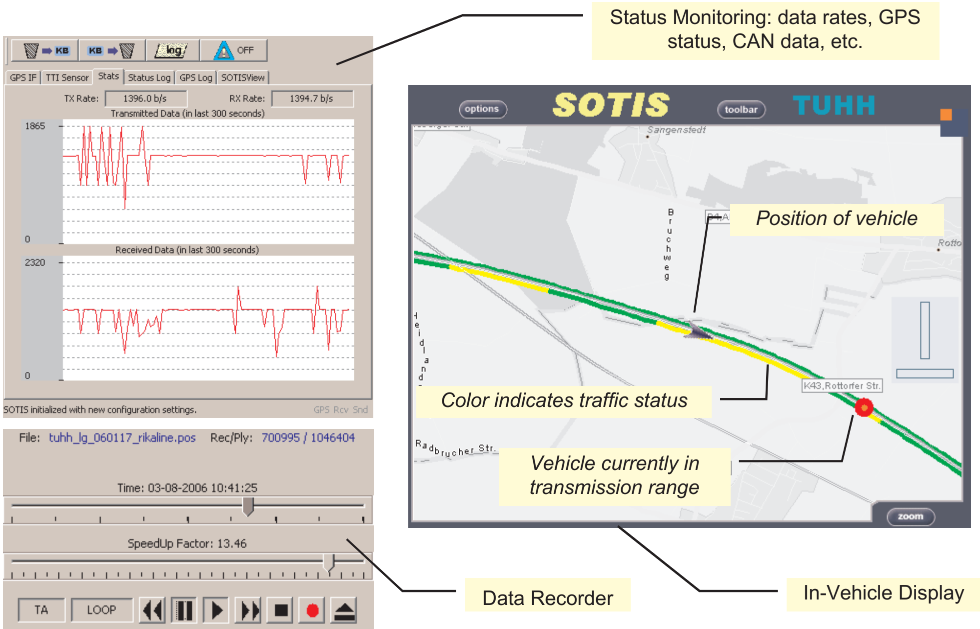


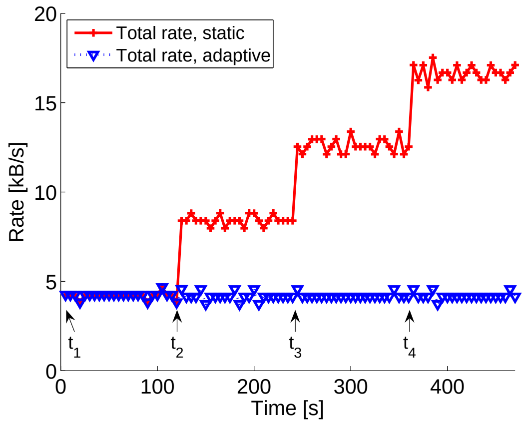
Figure 9.3: Information displays implemented in the experimental vehicles.

COMMUNICATION — Although the IEEE 802.11 WLAN standard is not targeted at vehicular communication and has performance deficiencies in vehicular city scenarios [ERW+03], it is used in the prototype simply because no other more suitable transceiver is available at a comparable cost. Furthermore, measurements in vehicular environments demonstrate that even without modifications, WLAN hardware is suitable for most IVC scenarios (see Section 2.3). Here, commercial IEEE 802.11b wireless LAN cards are employed (DSSS, 1 Mbit/s mode with DBPSK).

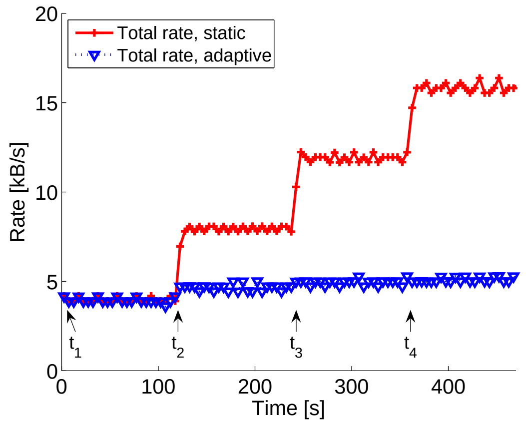
9.1.3 Test Results

Typical scenarios have been successfully tested with the prototype system in various parts of northern and central Germany: Gathering traffic information in each vehicle, information dissemination in a line of vehicles and information dissemination onboard a vehicle on the opposite lane.

Furthermore, a specific scenario involving four prototype nodes has been evaluated: The four vehicles are located close to each other (total connectivity). At the beginning, all nodes are switched off. Then, the nodes are activated consecutively: At time $t_1 = 0\,\mathrm{s}$, Node 1 starts sending, at $t_2 = 120\,\mathrm{s}$ Node 2, at $t_3 = 240\,\mathrm{s}$ Node 3,



(a) Simulation results (ns-2)



(b) Measurement results (prototype)

Figure 9.4: Comparison of simulation and measurement for the test scenario.

and at $t_4 = 360$ s Node 4. Thus, although no movement is present, the scenario imitates a dynamically increasing group of vehicles equipped with the system. At each node, the rates of transmitted and received data packets are measured. The prototype is tested in two configurations:

- **Static broadcast interval:** Nodes are transmitting with a static inter-transmission interval, similar to the simulative evaluations in Section 6.3. One UDP packet is sent every 350 ms.

- **Adaptive broadcast interval:** The inter-transmission interval is adapted using the Provoked Broadcast technique. It is implemented identically to the simulations in Section 6.4. In particular, the parameters for adaptation are the same (Table 6.6). The default inter-transmission interval is set to 350 ms.

For both configurations, the UDP payload size is 1400 bytes. The same scenario with both configurations was also evaluated by network simulation.

Figure 9.4 compares the results of the simulations with the prototype measurements. For both cases (static and adaptive interval), the total data rate observed at a node (sum of received and transmitted rates) is plotted over time. The symbol t_i indicates the time at which Node i is activated. For the static interval, the data rate increases linearly with the number of active nodes. If the adaptive system is used, the total data rate does not increase significantly if a new node at a similar same location is activated: The nodes have a similar view on the local environment and the observation of the transmissions of identical data by other nodes causes an adaptive increase of the transmission interval.

In general, the measurement results are in good accordance with the simulations. In 9.4(b), a slight increase of the total rate is observed at t_2 for the adaptive system, which does not occur in the simulations. A possible explanation is that the additional delay for processing the data packets in the network protocol stack of the system in combination with the short default interval causes data packets to be transmitted which can be suppressed in the simulations.

9.1.4 Local Hazard Warning

The SODAD approach is targeted at the dissemination of non-critical data and cannot guarantee a specific delay or delivery probability. However, it can, e.g., be used to disseminate hazard warnings in a local area that increase the safety of a driver. In order to demonstrate this type of application, a simple local hazard warning scheme is implemented within the SOTIS application.

A vehicle detects a potentially hazardous situation by monitoring information on the CAN bus: If an unusually high brake pressure, a released airbag or an activation of the hazard-warning signal flasher is detected, it starts to periodically transmit a short data packet including information on the location, road, road-side, time and type of hazard. Furthermore, it sets a flag in the segment information $s_{n,i}$ indicating that a hazard occurred.

In this way, a driver close to the hazard (i.e. in transmission range) is informed in detail with a low delay and a very high delivery probability due to large number of redundant transmissions of the short hazard warning packet. Figure 9.5 illustrates the hazard warning. And due to SODAD, the information that a potential hazard is at the specific segment is disseminated in a large range so that approaching drivers are aware of the situation very early.

9.2 *Proposal for UFB Integration in IPv6*

Next generation systems for Inter-Vehicle Communication (IVC) will most likely be based on an IP architecture [HBL+01, ZR03]. The IPv6 protocol [DH98] has emerged as the prevalent IP version able to meet the requirements in the ITS sector and is considered by the majority of IVC and RVC related projects in Europe, America and

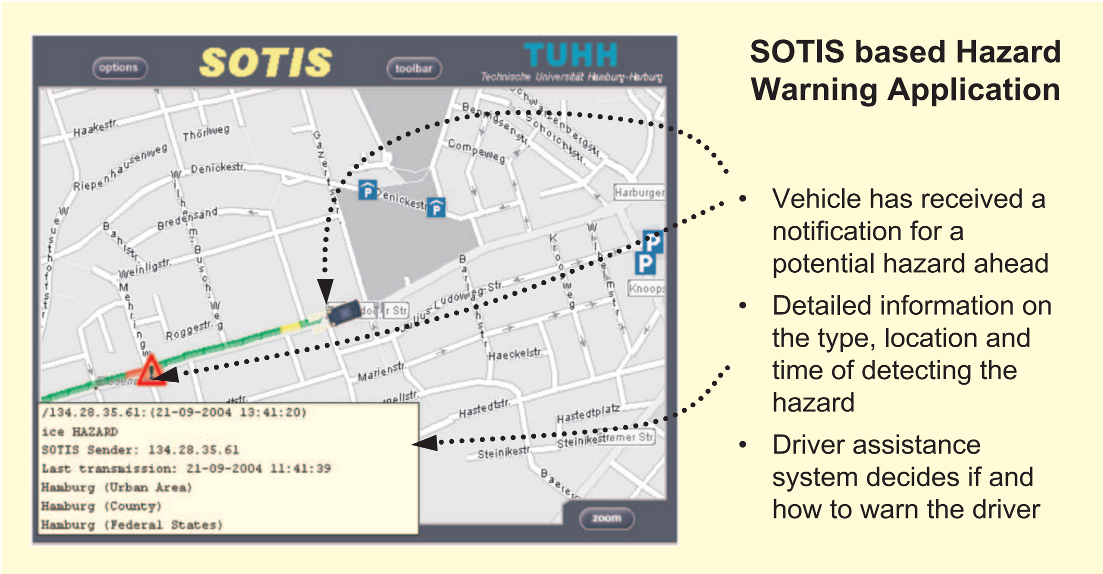


Figure 9.5: Experimental implementation of local hazard warning based on SOTIS.

Asia [Ern06]. A main reason is that an IVC system with IP network layer can easily be integrated in the existing IP networks.

Therefore, this section outlines a simple extension of the IPv6 protocol which implements the proposed UFB scheduling scheme developed in the last chapter. It is backward-compatible with existing hard- and software: Components not implementing UFB functionality simply forward the data packets in the usual IPv6 manner, i.e. schedule all data packets with the same priority. This is an important requirement since in this way IP based components in the in-vehicle network [MUM03] do not need to be modified. It is sufficient if the IP stack at the wireless IVC interface supports the proposed IPv6 extension for UFB.

9.2.1 Internet Protocol Version 6

Compared to its predecessor IPv4, IPv6 has several advantages, including an extended address space (128-bit instead of 32-bit) and a simplified fixed-length header that can be processed very efficiently. Particularly attractive features for IVC are the integrated support for anycast, mobility and address autoconfiguration of hosts.

The standard IPv6 header format is illustrated in Figure 9.6. It consists of eight fields [DH98], which are used in any IPv6 conform data packet. *Version (Vers)* is

Figure 9.6: Basic header of an IPv6 data packet.

a 4-bit field with the protocol version number, set to 6. *Traffic Class* is an 8-bit field specifying the class/priority of a data packet. In an IVC scenario, it can be used to distinguish different static priorities of applications, e.g. comfort and safety relevant. The 20-bit *Flow Label* field can be used to label sequential data packets for which a specific treatment is requested.

Payload Length specifies length of the payload in bytes.[2] An 8-bit selector, the so-called *Next Header* field, indicates the type of header immediately following this IP header. *Hop Limit* is the number of hops that this packet should be forwarded. For an IVC application which performs forwarding solely on the application layer, it is set to one. Applications which use the proposed SNF module set this field to a value larger than one. The 128-bit fields *Source Address* and *Destination Address* identify the IP layer source and destination of this data packet.

Besides this fixed header, an IPv6 data packet can contain multiple optional IPv6 extension headers. The type of the extension header is specified by the Next Header field in the preceding header. If the basic header is not followed by any extension header, the *Next Header* field has the value 59, according to the IPv6 standard.

Extension headers are always processed in the order in which they appear in the packet. Each extension header is a multiple of 8 bytes long. A full implementation of

[2]An implementation on an architecture with 8 bits per byte is assumed, therefore the terms *byte* and *octet* are used synonymously in the following.

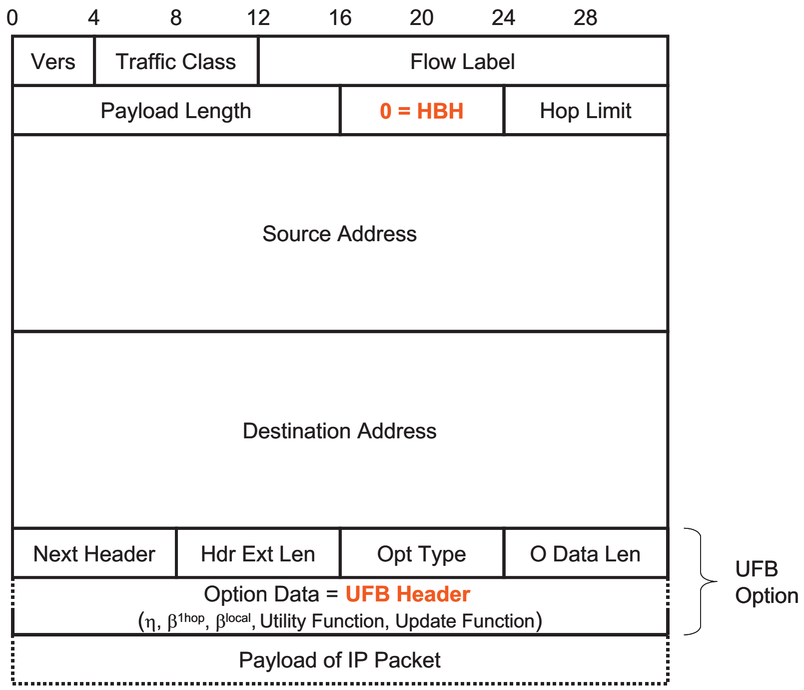


Figure 9.7: IPv6 data packet with extension header for context-aware packet scheduling.

IPv6 supports six types of extension headers: Hop-by-Hop Options, Routing (Type 0), Fragment, Destination Options, Authentication and Encapsulating Security Payload.

9.2.2 IPv6 Extension for UFB

As described in Chapter 8, for UFB one or more descriptors are included in each data packet. In the proposed IPv6 extension, these descriptors are inserted in form of a special *IPv6 Extension Header*. A host implementing the UFB packet scheduling reads the descriptors in the IPv6 Extension Header in order to determine the priority of a data packet depending on the local situation of the node. Routers and hosts which do not implement UFB simply ignore the descriptors and forward the data packets like regular IPv6 packets.

For UFB, the utility and the update function need to be evaluated at every hop. Therefore, a *Hop-by-Hop (HBH) Option* extension header (indicated by a Next Header value of 00) is used, as shown in Figure 9.7. If more than one extension header are included in an IPv6 packet, the HBH extension header is inserted first. The basic header is followed by the *Next Header* field, the *Extension Header Length* and the *Options* field. The variable length *Options* field consists of one or more Type-Length-Value (TLV) encoded options.

A new *Option Type* called *UFB Option* is defined. The binary value of this new option type is 0000 1111 (0x0F in hexadecimal notation). The way this option is processed in IPv6 nodes is the following [DH98]:

- The highest order two bits specify the action that must be taken by a node which does not implement the respective option type. Since these bits are both zero for *UFB Option*, a node not implementing UFB scheduling skips over the descriptor and continues processing the header and packet in the usual way.

- The next bit indicates if the option changes en-route, which is not the case for *UFB Option*.

- The last five bits are an arbitrary value which are unique for this option type. For large scale deployment of UFB scheduling, this value would need to be allocated by the Internet Assigned Numbers Authority (IANA) [ian].

For *UFB Option*, the option data length is variable and depends on the number and type of descriptors in the encoded utility and update functions. Descriptors are also TLV encoded and handled by the UFB scheduler which is usually implemented within the network layer of a node. With respect to the IPv6 integration, the format which is used for encoding the descriptors is irrelevant and therefore not described here. Basically, the same encoding as in the UFB performance evaluation is used (Section 8.7.1). The length of the *Options* field is padded so it is a multiple of 8 bytes.

In total, for implementing UFB packet scheduling in a node, only a small modification of the IPv6 layer is necessary in order to hand the descriptors encoded in the *UFB descriptor* option to the UFB packet scheduler. Obviously, an UFB packet-scheduler also needs to be implemented at the node. Since its implementation is independent of the IP layer, the detailed description is also omitted. No changes of the IPv6 standard itself are required.

9.2.2.1 Application Interfaces

In order to provide the UFB scheduler with the required update and utility functions, a suitable interface for applications needs to be provided. Two different kinds of interfaces are proposed:

1. Using an extended network socket interface, UFB-aware applications can explicitly configure the optimal scheduling for their data. Each data packet transmitted is supplemented with the adequate update and utility functions when it is handed from the application to the network protocol stack.

2. Legacy applications and other applications not requiring explicit control over the UFB scheduling can use the conventional network sockets. Since in this case the update and utility functions are not specified by the application, they can either be assumed to be static for a socket (e.g. depending on port and address) or be set by a specific classification module on the network layer.

In this way, specialized VANET applications as well as legacy applications expecting the conventional socket communication are supported.

9.3 Emulation of Vehicular Ad Hoc Networks

Conventionally, two methods are used for the evaluation of new communication techniques: network simulation and experimental implementation. By simulation, complex scenarios can be investigated and reproducible results are obtained. However, the required level of detail for the simulation model to achieve realistic results is hard to verify. Furthermore, simulation requires a specific implementation of the investigated system inside the simulation environment and does not allow to demonstrate the system behavior in reality. An experimental implementation avoids these drawbacks but leads to high costs for scenarios involving multiple nodes. In case of a VANET, the exact conditions of an experiment are also non-repeatable, e.g. since the wireless propagation depends on the positions of the individual vehicles as well as persons and objects in the environment.

Network emulation, a hybrid method combining simulation and testbed implementation, evaluates an experimental implementation in a simulated environment. In this way, most advantages of both methods are retained [JS04, KMJ00]: On the

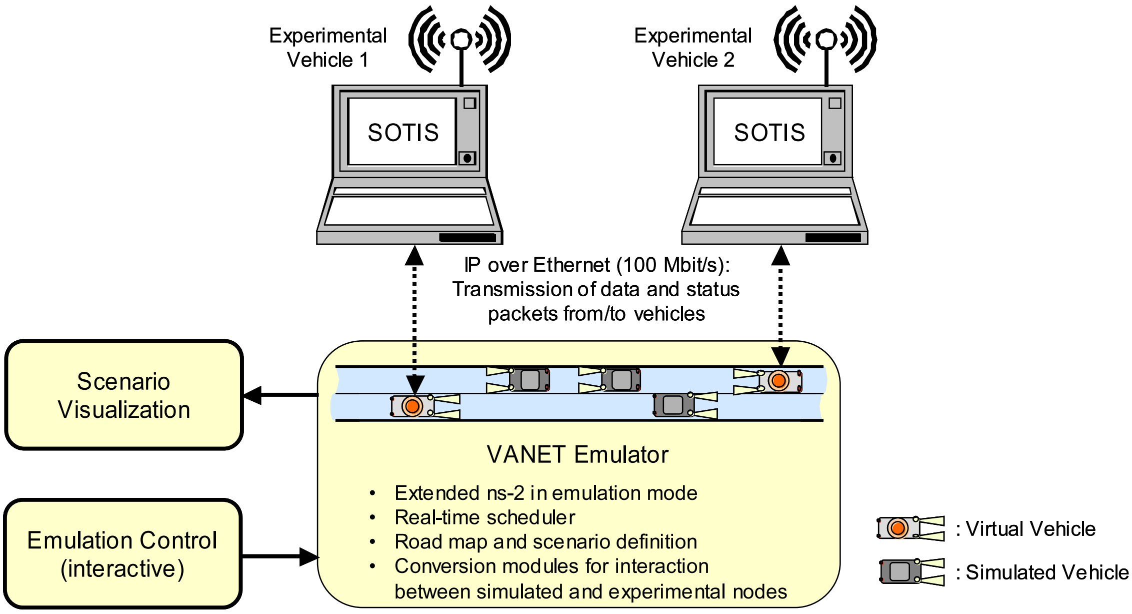


Figure 9.8: Testing two experimental implementations in an emulated vehicular ad hoc network.

one hand, real applications are executed and therefore a high realism of the generated data traffic and application behavior is guaranteed. On the other hand, the evaluation is repeatable, detailed experimental control and trace logging are available and scenarios with a relatively large number of nodes can be evaluated.

9.3.1 Concept for VANET Emulation

For the emulation of fixed and conventional wireless networks, several solutions are already known, e.g. distributed network emulators such as EMPOWER [NZ03] or extensions of ns-2 for the emulation of wirline networks [Fal99] and ad hoc communication [KMJ00]. However, the emulation of VANET scenarios imposes additional challenges: The movement pattern of a vehicle and the data disseminated by a VANET application depend on the road network. Thus, a consistent representation of the road map of experimental and simulated vehicles has to be guaranteed. Also, the information on the position of the vehicle available in the simulation needs to be identical to the knowledge of the experimental implementation. Furthermore, to allow the interaction between simulated and experimental VANET applications, suitable support needs to be provided by the VANET emulator.

The developed solution for VANET emulation is illustrated in Figure 9.8: The scenario is coordinated by a central system, the VANET emulator. It is based on the ns-2 emulation mode [Fal99], which is extended with the required functionality to handle the emulation of vehicular ad hoc networks. The emulator is configured with a detailed description of the scenario, including a description of the road network. In order to be able to guarantee consistency with the map used in the experimental systems, this road network description is generated automatically based on the digital vector data used in the experimental systems.

An emulation scenario consists of one or more experimental and a variable number of simulated vehicles. Inside the emulator, an experimental vehicle is represented by a *virtual vehicle*. A vehicular traffic model updates the positions of virtual and simulated nodes periodically using the information on the road network and mutual influence of the vehicles. The experimental systems are attached to the emulator by a high speed wireline network. Using this link, data packets generated at the experimental vehicles are injected in the emulator at the respective position of the corresponding virtual vehicle. Vice versa, all data received by the virtual vehicle in the emulator is transmitted to the experimental vehicle. Since the data rate available at the wireline connection to the experimental nodes exceeds the simulated wireless rates by orders of magnitude, the additional delay occurring at this link can be neglected.

Furthermore, the emulator periodically sends status packets to the experimental vehicle which contain information on its current position and velocity. Via the sensor interface, this information is provided to the application in a transparent way. Thus, all position information is determined by the emulator and a consistency can be guaranteed.

The current situation in the emulated network is visualized online with a delay of about 1 s in a scenario visualization tool. The emulation can also be controlled interactively. This can be done by a specific control component or by information sent by the experimental vehicle via status packets to the emulator. For example if the application at the experimental vehicle transmits an emergency notification, the virtual vehicle in the emulator stops and thus generates a traffic jam.

Based on the current state in the emulation environment, experimental nodes receive exactly those data packets which they would be able to receive in the simulated situation.

Properties evaluated by the emulator include

- distance between sender and receiver and the resulting signal power depending on the configured radio propagation model (Free space, two-ray model or log-normal shadowing are supported.),
- data packet collisions,
- data link and physical layer behavior (backoff, etc.).

Simulation time and real-world time are synchronized by using a specific real-time scheduler. It keeps track of the time difference between simulated and real time and warns if a user-defined threshold is exceeded.

9.3.2 Implementation

Due to the fact that the VANET emulation is implemented in the same environment as the simulations for performance evaluation (Section 6.3), many components are reused. In particular, the simulated vehicles and the cellular-automaton based vehicular traffic simulation are identical. For virtual vehicles, only position, velocity, and 802.11 PHY/MAC layer are simulated since all higher layers are provided by the experimental system itself.

The connection of a virtual vehicle to its experimental counterpart is achieved by three new entities (agents): A position agent periodically transmits the current position, time and velocity as sensor readings to the real node. Two VANET application agents are responsible for sending/receiving data packets from/to the experimental nodes. Since the data packet formats in emulator and experimental implementation differ, these application agents also take care of the required conversion of data packet formats to allow interaction of simulated and experimental vehicles. Network objects [KMJ00] are used to access live traffic in form of UDP/IP data packets.

Synchronization of the virtual time used for discrete event simulation and wall time is achieved by the real-time scheduler in a straightforward way [Fal99]: In a continuous loop, the scheduler first checks if any events with a deadline before the current real time exist. These are executed and a warning is issued if the deadline has been violated by a significant amount of time. Then, the scheduler waits until either a network I/O event occurs (i.e. a data packet is received from one of the

Table 9.1: Parameters for network emulation tests.

Hardware	
VANET Emulator	Intel Celeron, 1100 MHz
Experimental Nodes	Intel Pentium III, 800 MHz
Local Network	Ethernet, 100 Mbit/s

Emulator: Communication	
Radio Propagation Model	two-way ground
MAC Model	IEEE 802.11 (ad hoc mode)
PHY Data Rate	1 Mbit/s
Transmit Range R	1 km
VANET Application	SOTIS

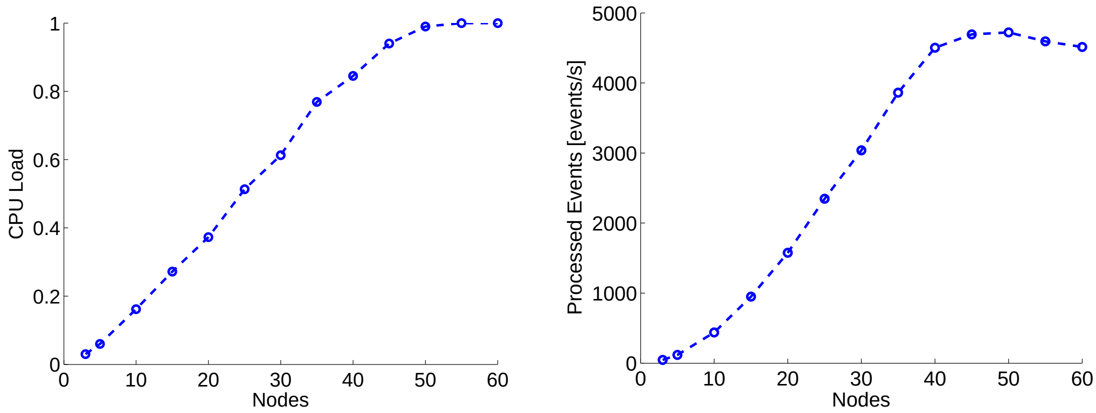
Emulator: Vehicular Traffic Model	
Road Length	15 km
Number of Lanes	1 per direction
Deceleration Probability	0.4 (no velocity-dependent randomization)
Desired Velocity	142 km/h
Number of Vehicles	2 experimental, 1 . . . 58 simulated

experimental nodes) or the deadline of a future event is reached. Whichever event occurs first is processed and the loop restarts.

9.3.3 Test Results

An important performance criterion for a VANET emulator is the number of simulated nodes which can be handled simultaneously, i.e. the complexity of an emulated scenario. In general, it strongly depends on the computational power of the network emulator: Since it needs to simulate all events occurring in simulated nodes in a time not exceeding the real-time, it is usually the bottleneck.

In the following, the results from tests with two experimental and N simulated vehicles are reported. The number of simulated vehicles N varies from 1 to 58, leading to a more and more complex emulation scenario. During the emulation, all



(a) CPU Load

(b) Number of Processed Events

Figure 9.9: Resulting CPU load of emulator and number of processed events per second for an emulation scenario with two experimental and a varying number of simulated nodes.

vehicles are in transmission range of each other – leading to a worst case situation in terms of computational complexity. At each simulated and each experimental node, a single SOTIS application is active generating one UDP broadcast data transmission per second. Table 9.1 lists the remaining parameters for VANET emulation.

During the tests, the average CPU load at the emulator and the number of processed events per second are recorded. As illustrated in Figure 9.9(a), the CPU load increases almost linearly with increasing number of nodes in the beginning. Similarly, the number of processed events per second goes up (Figure 9.9(b)). This continues until about 40 nodes are in the emulated scenario and the emulator is at a load of 0.8. When the number of nodes increases even further, the load is approximately 1.0 and the number of processed events starts to decline.

These results show that the emulator can handle a scenario with more than 35 nodes within the given real-time constraints with this hardware configuration. When the number of nodes exceeds this value, the emulator cannot process all events in time: The number of processed events drops, the real-time scheduler of the emulator reports warnings and the emulation becomes more and more inaccurate.

An emulation scenario with 30 and more nodes is very valuable to test and demonstrate experimentally implemented VANET applications in a controlled environment. The number of vehicles supported in an emulation scenario can be increased further by using a machine with more computational power for emulation.

9.4 Summary of Chapter

In this chapter, an experimental implementation of several VANET techniques developed throughout this thesis is presented: The full functionality of a typical VANET application, the proposed self-organizing traffic information system, has been implemented using off-the-shelf hardware. Using conventional WLAN for ad hoc communication, it disseminates information on the local traffic situation using SODAD and the heuristic Provoked Broadcast technique. Available information on the traffic state and potential hazards in the local area is visualized on a commercial vector map. The experimental results for a scenario involving up to four experimental vehicles are in good accordance with the simulation results for an identical scenario. In addition, an integration of UFB scheduling in IPv6 has been outlined and a VANET emulator combining simulation and experimental implementation in a controlled environment has been developed. It allows to test a real VANET application in a complex scenario involving more than 35 simulated vehicles in real-time on modest standard hardware.

X

Conclusions

In the automotive domain, a large range of safety and comfort applications can benefit from communication because information can be acquired for an area exceeding the range of onboard sensors and human perception by far. In contrast to the established forms of vehicular communication, a Vehicular Ad Hoc Network (VANET) can provide direct information exchange between vehicles. For two vehicles in mutual transmission range, this allows data transmissions with very low delays. No infrastructure is required and as a result, no service charges apply for communication. And since the network is provided by the vehicles themselves in a self-organizing manner, it is available whenever vehicles equipped with the VANET communication system are in transmission range.

However, this dependence on other equipped vehicles implies a significant challenge for market introduction of such a technology. The first part of this thesis has therefore investigated the constraints of data dissemination in VANETs, with a focus on situations where only a low number of vehicles is equipped with the ad hoc communication system. A main result was that conventional multi-hop routing techniques used in other types of ad hoc networks fail to disseminate information in a large range if less than 10-20 % of all vehicles are equipped. In contrast, if vehicles on the opposite lane transport the information onboard while no communication partner is in transmission range, the VANET can provide information for a large range even in case of low market penetration. For this combined approach, an analytical approximation for the speed of information dissemination was derived. It indicates the obtainable speed depending on road traffic density and penetration of the ad hoc technology.

Based on these observations, a segment-oriented technique for abstracting and disseminating data was proposed. It uses a digital map onboard the vehicle to aggregate information values sensed by multiple vehicles for a segment of the road. The vehicles broadcast their currently available information to all communication partners in local transmission range. A store-and-forward technique on the application layer is applied to transport the data while no other equipped vehicle is in direct transmission range.

The scheme was evaluated by network simulation including a suitable microscopic vehicular traffic model. In accordance with the analytical approximation, it can acquire information for a large area even if only a low fraction of all vehicles is equipped. The average age of information available for a specific location increases linearly with the distance. Furthermore, the influence of the vehicular traffic and radio channel model as well as the medium access technique was considered. It was shown that the approach is robust against errors on the lower communication layers, e.g. the achieved speed of information dissemination in case of a non-ideal IEEE 802.11 MAC is similar to the result for an ideal medium access scheme.

As a typical application for this dissemination technique, a self-organizing traffic information system was presented. It provides detailed traffic information for a range of more than 50 km even if only 1-2% of all vehicles are equipped with VANET technology. The average age of the available information is considerably lower than for conventional centralized traffic information systems.

Segment-oriented abstraction of data was originally done based on a commercial road map stored onboard the vehicle. In addition, an extension was presented which uses a decentralized scheme for self-generating the road map onboard the vehicle by combining information on the tracks driven by other vehicles. This allows the implementation of the data dissemination technique even if no pre-installed map is available.

The other focus of the thesis was a decentralized, self-organizing scheme for congestion control in a VANET. It is required to avoid overload conditions and increase the efficiency of data dissemination. An initial evaluation demonstrated that even a simple heuristic solution, which adapts the inter-transmission interval in cases of a high density of equipped vehicles, clearly outperforms a non-adaptive approach.

For an application independent systematic implementation of congestion control, a suitable communication architecture was introduced. Its main idea is a new concept for estimating the utility of a broadcasted data packet for the VANET. Each node claims a fair share of the locally available bandwidth which is proportional to the utility of the packet. The data rate is adapted on a per-packet basis – allowing an instantaneous reaction to the high rate of topological changes.

Detailed network simulations were performed to evaluate the advocated utility concept. The utility-fair broadcast scheme significantly improves the performance of data dissemination. Data packet collisions are reduced and the rate available for an individual application is adapted dynamically. In order to avoid the requirement that all forwarding vehicles use the same VANET application, a store-and-forward module has been proposed. It allows the deployment of manufacturer-specific applications while still utilizing all vehicles for data dissemination. Depending on the scenario, this reduces the average delay by more than 50 % and significantly increases the number of received messages.

The proposed data dissemination techniques and the VANET based self-organizing traffic information system were additionally integrated in an experimental system. It demonstrates that an implementation on currently existing hardware is feasible. Test results for a scenario with four vehicles are in good accordance with simulation results. A VANET emulation environment additionally allows tests of the experimental implementation in a simulated environment in realtime.

Several conclusions can be drawn from these contributions. Driver assistance systems can benefit significantly from vehicular ad hoc communication even if only a small fraction of all vehicles is equipped with the ad hoc communication system. A controlled sharing of the wireless link is of major importance for the performance of the VANET. It can be implemented in an application independent manner, e.g. within the existing IPv6 protocol stack. If the deployment of manufacturer-specific VANET applications is desired, a generic store-and-forward module should be included. While safety applications require a high ratio of equipped vehicles and suitable solutions for data security, for non-critical comfort applications a large scale deployment in the near future is procurable.

A

Vehicular Traffic Models

The stochastic network model introduced in Chapter 3 considers the position and movement of individual vehicles. By assuming a specific number of all vehicles to be equipped with the ad hoc communication system, a realistic VANET topology for typical traffic situations is obtained. In order to asses the results for the different scenarios presented in this thesis, some background knowledge on traffic engineering and traffic simulation is required.

This appendix first outlines the necessary basics of vehicular traffic simulation and vehicular traffic engineering in general. Afterwards, the microscopic traffic model used for the highway traffic simulations – the cellular automaton model – is briefly presented, including its main algorithms for updating position and velocity of simulated vehicles.

A.1 Fundamentals of Traffic Flow Theory

The fundamental properties commonly used to characterize road traffic situations are traffic density, traffic flow (traffic flux), average velocity and headway.[1] The headway is defined as the time interval that elapses until the identical point on two consecutive vehicles passes a fixed point at the road. The average headway $\bar{z}$ is inversely proportional to the traffic flow.

The traffic density ρ describes the number of vehicles on a part of the road with a given length (usually per kilometer). Using the density-flow relation given in Eqn. A-1, the traffic flow $q(\rho)$ can be calculated as product of average velocity $\bar{v}$ and traffic density.

$$q(\rho) = \bar{v} \cdot \rho \tag{A-1}$$

[1]If not noted otherwise, the parameters are given per lane of the road.

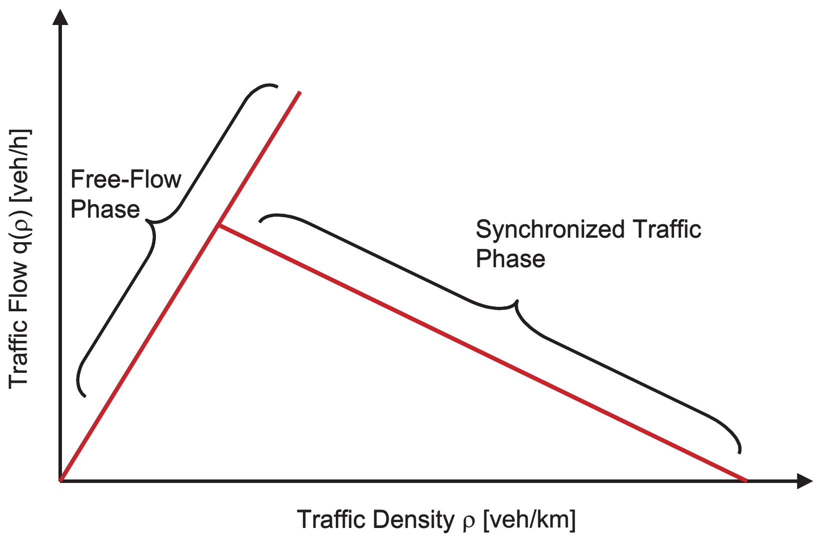


Figure A.1: Schematic illustration of the flow-density relation (fundamental diagram).

The traffic flow resulting of a specific traffic density is often plotted in a so-called fundamental diagram (Figure A.1). Two main phases of traffic can be distinguished [Kra88, Hel01]:

- free-flow phase and
- congested phase/synchronized traffic.

In a low density traffic situation, the vehicles are not influenced by other road users and move at their desired velocity $v_{\max}$, which is usually near the speed limit for the considered road. Therefore, the traffic flow increases linearly with the traffic density, the slope of increase is determined by $v_{\max}$. This type of traffic is termed *free-flow traffic* and corresponds to the left branch in the schematic fundamental diagram in Figure A.1.

If the traffic density increases further, the vehicles start to interact and the velocity is determined by other vehicles and safety considerations. As a result, the traffic flow $q(\rho)$ decreases with increasing ρ. This *congested phase* is called *synchronized traffic* (Figure A.1). Note that near the maximum traffic flow $q_{\max}$, which is in the order of $q_{\max} \approx 2500$ veh/h for highway situations, the traffic flow is not a unique function of the density. Figure A.2 shows an example for an empirically measured density-flow relation on a German highway.

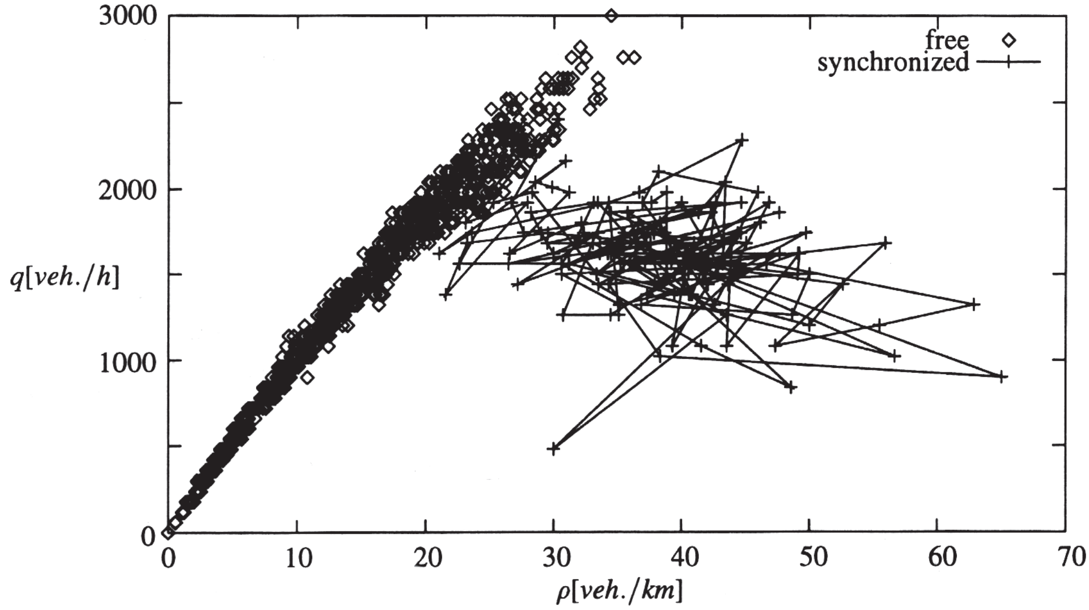


Figure A.2: Fundamental diagram measured at the German A43 near Bochum.
Published in [Kra88], reprinted with kind permission of German Aerospace Center (DLR), Köln.

Finally, if the traffic density is increased even further, it leads to a stop-and-go traffic where vehicles inside the jams come to a complete stop [CSS00]. The traffic flow is nearly zero and the maximum traffic density ρ_{max} determined by

$$\rho_{\text{max}} = \frac{1}{l_{\text{veh}}} \tag{A-2}$$

is achieved. Here, l_{veh} denotes the average space occupied by a vehicle.

A.2 Overview of Vehicular Traffic Models

A wide range of different traffic models has been developed in the traffic engineering community. Based on the level of detail which is modelled, vehicular traffic models can be classified in four categories [HB01, Hel01]: macroscopic, mesoscopic, microscopic and submicroscopic traffic models.

Macroscopic Traffic Models

Macroscopic traffic models do not model individual vehicles but vehicular traffic as a whole. The aggregate traffic is considered analogously to a stream of gas or fluid and described by macroscopic variables such as density, flow and velocity. A set of partial differential equations is used to model the dynamics of the variables. Since in macroscopic models position and maneuvers of individual vehicles are not considered, a macroscopic traffic model is not sufficient for the VANET network simulations in this thesis.

Mesoscopic Traffic Models

In mesoscopic traffic models, the individual actions of the vehicles are considered but described in an aggregate form, e.g. by a probability density function. Therefore, the level of detail is between that of a macroscopic and that of a microscopic model.

A typical example for a mesoscopic model are headway distribution models, where the headway z is modelled as a random variable Z. A commonly used probability density function $f_Z(t)$ used to characterize Z is an exponential distribution [Pap91]:

$$f_Z(t) = \begin{cases} qe^{-qt}, & t \geq 0; \\ 0, & \text{otherwise.} \end{cases} \tag{A-3}$$

This choice is due to the assumption of statistical independent, identically distributed inter-arrival times – leading to a Poisson arrival model and therefore an exponentially distributed headway. Its expected value, the average headway, is the reciprocal of the traffic flow q:

$$\mathrm{E}\{Z\} = \int_{-\infty}^{\infty} t f_Z(t) \;\, \mathrm{d}t = \frac{1}{q} = \bar{z} \tag{A-4}$$

This simple exponential model is widely used in the literature, but not very accurate in high density traffic situations, since it does not take platooning into account. More complex probability functions such as the bunched exponential distribution can be used in this case [Ebn05a, AC94].

These mesoscopic traffic models allow the calculation of estimates for the expected traffic situation and the resulting performance of a vehicular ad hoc network. Therefore, they are mainly applied in Chapter 5 when general VANET characteristics are derived. However, since properties of individual vehicles are known only in a probabilistic way, mesoscopic models are not suitable for the detailed discrete event network simulations in later chapters, where the exact position of each simulated vehicle has to be determined.

Microscopic Traffic Models

Microscopic traffic models [CSS00, HB01] describe the actions of vehicles individually. The properties of vehicular traffic emerge from simple interactions between vehicles[2]. The type of interaction between two vehicles is determined by their position, velocity, headway and similar factors. A set of (usually very simple) rules defines the way in which vehicles react to a situation depending on their current state. Two commonly used types of microscopic models are car-following models [GT92] and cellular automaton based approaches.

Car-following models define the behavior of an individual car in form of a response (acceleration or deceleration) resulting from a specific stimulus and sensitivity. Common stimuli include the distance and velocity difference between leading and following vehicle [HB01].

$$a_n(t+T) = \gamma(v_{n-1}(t) - v_n(t)) \tag{A-5}$$

Equation A-5 is an example where the acceleration a at $t+T$ depends on the velocity difference at time t. Here, T denotes the reaction delay of the driver. The sensitivity $\gamma(\cdot)$ is specific for a car-following model, a simple follow-the-leader model adapts to the velocity of the vehicle ahead with the following $\gamma(\cdot)$.

$$\gamma(t+T) = \frac{1}{\tau}[v_{n-1}(t) - v_n(t)] \tag{A-6}$$

The parameter τ is a sensitivity coefficient. More complex stimulus functions, potentially depending on the state of vehicle and driver – as done in psycho-spacing/Wiedemann models – can simulate the behavior of an individual vehicle and the traffic as a whole with more detail but also increased (computational) complexity.

The second common microscopic type, cellular automaton based traffic models, also considers positions and parameters for each vehicle. However, it is a discrete

[2]Microscopic models sometimes even refer to them as "particles".

model which can be implemented very efficiently in computer simulation. Therefore, it is presented in more detail in Section A.3. Since in microscopic traffic models position and velocity of each individual node are available, this type of model is also used for the VANET simulations in this thesis.

An even higher level of details is offered by submicroscopic traffic models, which additionally consider the vehicle's subunits and interaction with its surroundings [HB01], e.g. for estimating the abrasion of specific components. However, this level of detail is not required for modelling the VANET topology and would significantly increase the required computational power for simulation.

A.3 Cellular Automata for Microscopic Traffic Modelling

A relatively new microscopic traffic model, which was developed in the 1990s, is the Cellular Automaton (CA) or Nagel-Schreckenberg model [NS92, SS93, CSS00]. It divides each lane of the road in cells of equal length, usually 7.5 meters[3]. A cell can either be occupied by at most one vehicle or be empty. Additionally, for each vehicle the velocity v_n in terms of cells per simulated time step is stored. This discrete representation of the spatial situation is updated with a set of simple rules in time steps of usually 1 s of simulation time.

The basic CA model [NS92] uses only the following four rules, which are applied to all vehicles in parallel:

Rule 1 - Acceleration: If a vehicle has not yet reached its desired velocity v_{max}, its velocity v_n is increased by 1.

$$v_n \leftarrow \begin{cases} v_n + 1, & v_n < v_{\max}; \\ v_n, & \text{otherwise.} \end{cases} \tag{A-7}$$

Rule 2 - Deceleration: For each vehicle n, the distance (gap in number of cells) g_n to its preceding vehicle $n+1$ is calculated. A vehicle ahead leads to a deceleration if g_n is low.

$$v_n \leftarrow \min(v_n, g_n) \tag{A-8}$$

[3]A cell length of 7.5 m is used since this is approximately the length of vehicle plus headway in a traffic jam.

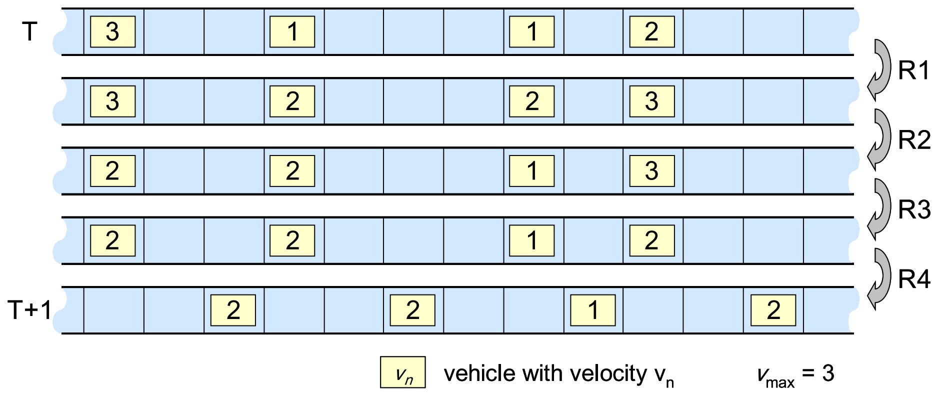


Figure A.3: Example for the application of the four rules (R1 to R4) of the basic Nagel-Schreckenberg traffic model.

Rule 3 - Randomization: The random component of the behavior of a driver is considered by the parameter p_{dec}, which is the probability for a random deceleration for vehicles with a velocity greater than zero.

$$v_n \leftarrow \begin{cases} v_n - 1, & \text{with probability } p_{\mathrm{dec}}; \\ v_n, & \text{with probability } (1 - p_{\mathrm{dec}}). \end{cases} \tag{A-9}$$

Rule 4 - Drive: The position of the vehicle is advanced by v_n cells.

For the transition from time step T to $T + 1$, all rules are applied consecutively, as illustrated in Figure A.3.

This basic CA model simulates single lane highway traffic. In order to increase its accuracy and allow modelling of multiple lane traffic, many extensions have been proposed in traffic simulation literature. Two extensions used in the traffic simulations in this thesis are presented in the following.

A.3.1 Extensions of the Nagel-Schreckenberg Model

The first extension of the Nagel-Schreckenberg model implemented for the simulations in this thesis is a slow-to-start rule, the so-called Velocity Dependent Randomization (VDR) [BSSS98]. VDR improves the restart behavior of stopped cars in traffic jam situations by varying the deceleration probability (Rule 3 in Section A.3) depending on the velocity.

$$p_{\mathrm{dec}}(v_n) = \begin{cases} p_0, & \text{for } v_n = 0; \\ p_{\mathrm{dec}}, & \text{otherwise.} \end{cases} \tag{A-10}$$

Choosing a $p_0 > p_{\text{dec}}$ leads to a higher probability for random deceleration of stopped vehicles (e.g. in a traffic jam) and thus a slow-to-start behavior.

A second extension are two-lane traffic rules [NWWS97], which model lane changes on highways with more than one lane per direction. Lane changing rules need to take two main aspects into account:

- Attractiveness: A lane change is attractive for a vehicle if the velocity on the alternative lane exceeds the possible velocity on the current lane.
- Security: A save lane change is only possible if the distance to the vehicles behind on the alternative lane is large enough.

Depending on the respective traffic laws, further extensions might be required, e.g. on German highways passing is allowed only on the left lane.

The CA model used in this thesis implements the lange changing extensions proposed in [Neu00]. A symmetric lane changing rule is added to the basic Nagel-Schreckenberg model which considers attractiveness and safety: For each vehicle n, the gaps $g_n^{\text{alt,+}}$ in front of and $g_n^{\text{alt,-}}$ behind the cell corresponding to the current position on the alternative lane are calculated (analogously to Rule 2 in Section A.3). Since one cell would be occupied by the vehicle itself, the total gap g_n^{alt} on the alternative lane is

$$g_n^{\text{alt}} = g_n^{\text{alt,-}} + 1 + g_n^{\text{alt,+}} \tag{A-11}$$

The potential velocity on the alternative lane v_n^{alt} is calculated as in the basic CA model.

$$v_n^{\text{alt}} = \min\left[\min(v_{\max}, v_n + 1), g_n^{\text{alt,+}}\right] \tag{A-12}$$

Considering the current velocity v_{n-1}^{alt} of the following vehicle on the alternative lane, its maximum velocity $v_{n-1}^{\text{alt,max}}$ after the current time step is calculated.

$$v_{n-1}^{\text{alt,max}} = \max(v_{n-1}^{\text{alt}} + 1, v_{\max}) \tag{A-13}$$

A lane change to the alternative lane is performed with probability p_{change} if the following two conditions are fulfilled:

(1) $v_n^{\text{alt}} > v_n + 1$

(2) $g_n^{\text{alt,-}} \geq v_{n-1}^{\text{alt,max}}$

Here, the first condition tests if the lane is attractive, the second takes the safety aspect into account.

A.4 Traffic Simulation in VANET Performance Evaluations

For the simulative performance evaluations in Chapters 6 to 9, the open source network simulator ns-2 is extended with a Nagel-Schreckenberg CA traffic simulation. It includes the basic CA rules introduced in Section A.3 and all extensions of Section A.3.1. Arbitrary road topologies can be defined – purely artificial patterns as well as road way points converted from commercial digital vector maps. For this import of real road maps in the simulation environment, digital vector data provided by *NAVTEQ*® can be converted to suitable map descriptions for the simulator.

For the traffic simulation, vehicles equipped with the vehicular communication system as well as vehicles without communication are simulated and influence each other. While communicating vehicles are a variant of mobile nodes within the ns-2 environment (including a simulation of the complete network protocol stack), the remaining vehicles exist only in the vehicular traffic simulation. In order to support different types of vehicles (e.g. trucks and regular passenger cars), $v_{\max}$ can be set individually for each car in the simulation. The generated vehicular traffic patterns can additionally be used as an input for network emulation.

B

GPS Model

Positioning errors of GPS receivers are introduced by various factors such as ionospheric/tropospheric effects, inaccuracies in ephemeris data and of satellite clocks, receiver noise and multipath effects. Accurate modeling of GPS errors is therefore a challenging task, and various complex models exist. However, in the performance evaluations in Chapter 7 a very simple GPS error model is used, since it is assumed that in a real system GPS data can be augmented by vehicle dynamics data (e.g. read from the in-vehicle CAN bus). Therefore, a more detailed GPS error model would still not represent the expected positioning error accurately.

Thus, for simplicity, a 2D-normal distributed error is assumed which is unbiased and has the same variance σ_d^2 for both spatial directions. This leads to a Rayleigh distributed absolute error with an expected value of $\sigma_d\sqrt{\frac{2}{\pi}}$. As illustrated in Fig. B.1, this is only a rough approximation.

With this simple error model, the positions "jump" since the correlation in time is not taken into account. As in a GPS receiver, the obtained positions are therefore filtered. A simple Kalman filter is used, in which the current state of the vehicle is represented by the following state vector

$$\mathbf{X}(n) = \begin{bmatrix} p_x(n) \\ v_x(n) \\ p_y(n) \\ v_y(n) \end{bmatrix} \tag{B-1}$$

where p_x and p_y are the position x- and y-coordinates and v_x and v_y are the corresponding velocities. The state transition matrix $\mathbf{\Phi}$ is given by

$$\mathbf{\Phi} = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{B-2}$$

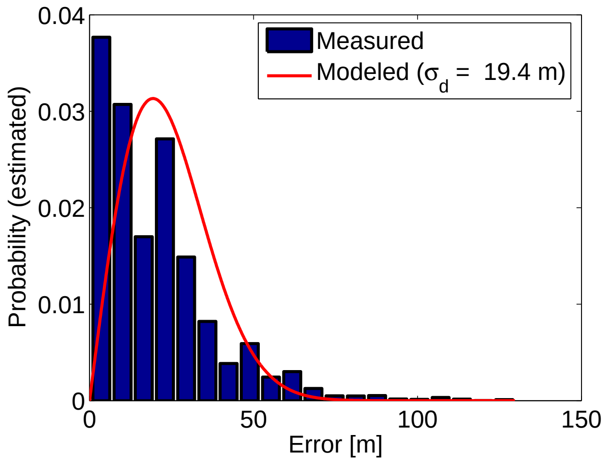


Figure B.1: Comparison of modeled and measured position error for a situation with relatively bad GPS reception.

Here, the constant T is the time between two state transitions. The changes in direction and velocity of the vehicle movement are modeled by the random process noise $\mathbf{U}(n)$:

$$\mathbf{U}(n) = \begin{bmatrix} 0 \\ u_x(n) \\ 0 \\ u_y(n) \end{bmatrix} \tag{B-3}$$

For simplicity, it is assumed that changes in velocity occur only right before a time step and that their influence on the position is reflected at the next time step. The only measurement used as input for the filter is the current position (x- and y-coordinates). Therefore, the observation matrix is

$$\mathbf{M} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{B-4}$$

and the observed measurement $\mathbf{Y}(n)$ is the determined by the true system state and the observation error $\mathbf{N}(n)$.

$$\mathbf{Y}(n) = \mathbf{MX}(n) + \mathbf{N}(n) \tag{B-5}$$

Now the only additional parameters of the Kalman filter, which need to be defined, are the covariance matrix $\mathbf{R}(n)$ of the measurement vector and the covariance matrix $\mathbf{Q}(n)$ of the system dynamics model noise vector. Due to the simplifying assumption that the components of $\mathbf{Y}(n)$ are independent, they are defined based on the variance σ_R of the measurement of a component and the variance σ_a of the velocity changes.

$$\mathbf{R} = \begin{bmatrix} \sigma_R^2 & 0 \\ 0 & \sigma_R^2 \end{bmatrix} \tag{B-6}$$

$$\mathbf{Q} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \sigma_a^2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_a^2 \end{bmatrix} \tag{B-7}$$

With these definitions, the standard Kalman estimation procedure [Bro98] can be applied.

Abbreviations and Symbols

Abbreviations

ACM	Association for Computing Machinery
AODV	Ad hoc On Demand Distance Vector
ASTM	American Society for Testing and Materials
BLR	Beacon-Less Routing
C2CC	Car-to-Car Communication
CA	Cellular Automaton
CAN	Controller Area Network
CD+CR	Collision Detection and Collision Resolution
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
DAB	Digital Audio Broadcast
DBPSK	Differential Binary Phase Shift Keying
DCF	Distributed Coordination Function
DQPSK	Differential Quadrature Phase Shift Keying
DSRC	Dedicated Short Range Communication
DSSS	Direct Sequence Spread Spectrum

DVB	Digital Video Broadcast
DVB-T	Digital Video Broadcast - Terrestrial
E911	Enhanced 911
EBU	European Broadcasting Union
E-SOTDMA	Extended Self-Organizing Time Division Multiple Access
FDMA	Frequency Division Multiple Access
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GRL	Geo-Reference List
GRP	Geo-Reference Point
GSM	Global System for Mobile Communications
IEEE	Institute of Electrical and Electronics Engineers
InVC	In-Vehicle Communication
IPv6	Internet Protocol Version 6
IS-95	Interim Standard 95
ISM	Industrial, Scientific and Medical
IVC	Inter-Vehicle Communication
LIN	Local Interconnect Network
LOS	Line-Of-Sight
MANET	Mobile Ad Hoc NETwork
MOST	Media Oriented Systems Transport
NLOS	Non-Line-Of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
PDA	Personal Digital Assistant
PDF	Probability Density Function

PHY	PHYsical layer
RDS	Radio Data System
RTS	Request To Send
SDMA	Space Division Multiple Access
SLAM	Simultaneous Localization and Mapping
SNF	Store-aNd-Forward
SODAD	Segment-Oriented Data Abstraction and Dissemination
SOTIS	Self-Organizing Traffic Information System
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TLV	Type-Length-Value
TMC	Traffic Message Channel
TPEG	Transport Protocol Experts Group
TTI	Travel and Traffic Information
UDP	User Datagram Protocol
UFB	Utility-Fair Broadcast
UMTS	Universal Mobile Telecommunications System
UTM	Universal Transverse Mercator
UTRA	UMTS Terrestrial Radio Access
VANET	Vehicular Ad Hoc NETwork
VDR	Velocity-Dependent Randomization
VRC	Vehicle-to-Roadside Communication
WAVE	Wireless Access in Vehicular Environments
WGS84	World Geodetic System 1984
WLAN	Wireless Local Area Network

Symbols

a	acceleration [m/s^2]
α	minimum angle for generating reference points [°]
B_C	coherence bandwidth [Hz]
$\hat{B}^\mathrm{eff}$	estimated effective data rate [B/s]
B^eff	effective data rate [B/s]
β_i	available effective data rate per node per utility [B/s]
β^local	locally common value for ratio of effective data rate to utility [B/s]
B_max	maximum effective data rate [B/s]
D_acc	positioning inaccuracy [m]
d_f	far-field distance [m]
D_grid	grid distance [m]
d_hop	progress towards destination (1-hop) [m]
d_i	distance to last vehicle in dissemination direction [m]
d_tx	distance to transmitting node [m]
$d_\mathrm{tx,max}$	maximum distance to transmitting node [m]
η_i	utility per byte for node i [1/B]
$f_\mathrm{D,max}$	maximum Doppler frequency [Hz]
$f_Z(t)$	probability density function of the random variable Z
γ	penetration of the ad hoc system ($\in [0.0, 1.0]$)
g_n	distance to preceding vehicle for vehicle n (CA model)
G_r	gain of receive antenna
G_t	gain of transmit antenna
s_i^rx	amount of data received in interval i [B]

s_i^{tx}	amount of data transmitted in interval i [B]
κ	density of equipped vehicles [veh/km]
λ	wavelength [m]
L	system loss factor
l_{veh}	average space occupied by a vehicle [m]
μ_X	expected value of random variable X
$\hat{\mu}_\eta$	estimate of expected value of η [1/B]
$\hat{N}$	estimated number of nodes in transmission range
N_{L}	number of lanes (sum over both directions)
n_{mhop}	number of hops
$\overline{N}_{\mathrm{TX}}$	expected value of number of ad hoc capable vehicles within range R
p_{dec}	probability for random deceleration (CA model)
P_{r}	received power [W]
P_{t}	transmitted power [W]
q	traffic flow (traffic flux) [veh/h]
q_{max}	maximum traffic flow [veh/h]
R	transmission range of ad hoc air interface [m]
r_i	instantaneous fair transmit rate for node i [B/s]
R_{CS}	carrier sense range [m]
ρ	road traffic density [veh/km]
ρ_{max}	maximum traffic density [veh/km]
R_{info}	information range [m]
$\overline{R}_{\mathrm{mhop}}$	expected value of multi-hop range [m]
R_{mhop}	multi-hop range [m]
S	number of segments in a data packet
s_i	size of data packet p_i [B]

$s_{\max}$	maximum packet size for UFB scheduling [B]
$s_{m,k}$	information value for segment k in message m
$t_{m,k}$	time-stamp for segment k in message m
$\tau_{\max}$	maximum channel tap delay [s]
T_{C}	coherence time [s]
T_{com}	communication time [s]
T_{gap}	time to close gap between two network parts [s]
θ	target load for UFB scheduling
$\overline{\tau}_{\mathrm{hop}}$	expected value of per hop forwarding delay [s]
T_{mhop}	time for multi-hop forwarding [s]
T_{mon}	time interval for monitoring the effective data rate [s]
$\bar{v}$	average velocity [m/s]
$v_{\max}$	desired velocity [m/s]
v_{mhop}	velocity of multi-hop information dissemination [m/s]
v_n	velocity of vehicle n in terms of cells per time step (CA model)
V_{rel}	relative velocity (random variable) [m/s]
$w_{m,n}$	weight of message m at node n
z	headway [s]
$\bar{z}$	average headway [s]

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Bibliography

[Abr70] Norman Abramson. The ALOHA System – Another Alternative for Computer Communications. In *Proc. American Federation of Information Processing Societies Conference*, volume 36, pages 295–298, 1970.

[Abr85] Norman Abramson. Development of the ALOHANET. *IEEE Transactions on Information Theory*, IT-31(2):119–123, March 1985.

[AC94] R. Akçelik and E. Chung. Calibration of the Bunched Exponential Eistribution of Arrival Headways. *Road and Transportation Research*, 3(1):42–59, 1994.

[AKR99] Ulrich Ann, Dirk Kügler, and Hermann Rohling. Analysis of Self-Organising Radio Systems for Position Reporting. *Journal of the Royal Institute of Navigation*, 52(2):196–202, 1999.

[Ann99] Ulrich Ann. *Selbstorganisierende Datenfunknetze für Verkehrsanwendungen*. PhD thesis, Braunschweig Carolo-Wilhelmina University of Technology, Braunschweig, Germany, 1999. (in German).

[ANS99] ANSI. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. ANSI/IEEE Standard 802.11-1999, 1999.

[ARP05] Maen M. Artimy, William Robertson, and William J. Phillips. Assignment of Dynamic Transmission Range based on Estimation of Vehicle Density. In *Proc. 2nd ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2005)*, pages 40–48, New York, NY, USA, 2005. ACM Press.

[ASSC02] Ian F. Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci. A Survey on Sensor Networks. *IEEE Communications Magazine*, 2002(8):102–114, August 2002.

[AST03a] ASTM E 2158-01. Specification for Dedicated Short Range Communication (DSRC) Physical Layer Using Microwave in the 902 to 928 MHz Band. Book of Standards Volume 04.03, 2003.

[AST03b] ASTM E 2213-03. Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems – 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Book of Standards Volume 04.03, 2003.

[BCL98] Giuseppe Bianchi, Andrew T. Campbell, and Raymond R.-F. Liao. On Utility-Fair Adaptive Services in Wireless Networks. In *Proc. 6th International Workshop on Quality of Service (IEEE/IFIP IWQOS'98)*, Napa Valley, California, USA, May 1998.

[Bec04] Marc Bechler. *Internet Integration of Vehicular Ad Hoc Networks*. PhD thesis, Technische Universität Braunschweig, Braunschweig, Germany, October 2004.

[BEH04] Jeremy J. Blum, Azim Eskandarian, and Lance J. Hoffman. Challenges of Intervehicle Ad Hoc Networks. *IEEE Transactions on Intelligent Transportation Systems*, 5(4):347–351, December 2004.

[BH02] Linda Briesemeister and Günter Hommel. Integrating Simple yet Robust Protocol Layers for Wireless Ad Hoc Intervehicle Communications. In *Proc. Communication Networks and Distributed Systems Modeling and Simulation Conference (CNDS)*, pages 186–192, January 2002.

[BHT+03] Scott Burleigh, Adrian Hooke, Leigh Torgerson, Kevin Fall, Bob Durst, Keith Scott, and Howard Weiss. Delay-Tolerant Networking – An Approach to Interplanetary Internet. *IEEE Communications Magazine*, 41(6):128–136, June 2003.

[Bri01] Linda Briesemeister. *Group Membership and Communication in Highly Mobile Ad Hoc Networks*. PhD thesis, School of Electrical Engineering and Computer Science, Technical University of Berlin, Germany, November 2001.

[Bro98] Eli Brookner. *Tracking and Kalman Filtering Made Easy*. Wiley-Interscience. John Wiley & Sons, 1998.

[BSSS98] R. Barlovic, L. Santen, A. Schadschneider, and M. Schreckenberg. Metastable States in Cellular Automata for Traffic Flow. *European Physical Journal B*, 1998(5):793–800, 1998.

[BTD06] Subir Biswas, Raymond Tatchikou, and Francois Dion. Vehicle-to-Vehicle Wireless Communication Protocols for Enhancing Highway Traffic Safety. *IEEE Communications Magazine*, 44(2):74–82, January 2006.

[CC05] Wai Chen and Shengwei Cai. Ad Hoc Peer-to-Peer Network Architecture for Vehicle Safety Communications. *IEEE Communications Magazine*, 43(4):100–107, April 2005.

[CeS+98] Thomas M. Chen, Alden W. Jackson (editors), Jerome H. Saltzer, David P. Reed, and David D. Clark. Commentaries on “Active networking and end-to-end arguments”. *IEEE Network*, 12(3):66–71, May 1998.

[Con03] LIN Consortium. LIN Specification Package Revision 2.0, 2003.

[Coo04] MOST Cooperation. MOST Specification Rev 2.3, August 2004.

[CS02] Ioan Chisalita and Nahid Shahmehri. A Peer-to-Peer Approach to Vehicular Communication for the Support of Traffic Safety Applications. In *Proc. 5th IEEE Conference on Intelligent Transportation Systems, Singapore*, pages 336–341, September 2002.

[CSS00] Debashish Chowdhury, Ludger Santen, and Andreas Schadschneider. Statistical Physics of Vehicular Traffic and Some Related Systems. *Physics Reports*, 329(4–6):199–329, May 2000.

[DFM05] Florian Dötzer, Lars Fischer, and Przemyslaw Magiera. VARS: A Vehicle Ad-Hoc Reputation System. In *Proc. 6th IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM'05)*, Taormina, Italy, June 2005.

[DH98] S. Deering and R. Hinden. RFC2460 - Internet Protocol, Version 6 (IPv6) Specification (draft standard). Standards Track, December 1998.

[Ebn05a] André Ebner. *Selbstorganisierende Datenfunknetze für Anwendungen im Straßenverkehr*. PhD thesis, Hamburg University of Technology, Hamburg, Germany, 2005. (in German).

[Ebn05b] Ebner A, Halfmann R, Lott M, Rohling H, Schulz E, Wischhof L, inventors; Siemens AG, assignee. Patent DE10334431B4: Verfahren zur Zeitsynchronisation von Mobilstationen in einem selbstorganisierenden Funkkommunikationssystem, June 2005.

[Ebn05c] Ebner A, Halfmann R, Lott M, Rohling H, Schulz E, Wischhof L, inventors; Siemens AG, assignee. Patent DE10340814B4: Verfahren zum Betreiben eines Funkkommunikationssystems mit einem Adhoc-Modus, September 2005.

[EGKM04] Patrick T. Eugster, Rachid Guerraoui, Anne-Marie Kermarrec, and Laurent Massoulié. Epidemic Information Dissemination in Distributed Systems. *IEEE Computer*, 37(5):60 – 67, May 2004.

[ER01] André Ebner and Hermann Rohling. A Self-Organized Radio Network for Automotive Applications. In *Proc.* 8^{th} *World Congress on Intelligent Transport Systems*, Sydney, Australia, October 2001.

[Ern06] Thierry Ernst. The Information Technology Era of the Vehicular Industry. *SIGCOMM Comput. Commun. Rev.*, 36(2):49–52, April 2006.

[ERW+03] André Ebner, Hermann Rohling, Lars Wischhof, Matthias Lott, and Rüdiger Halfmann. Performance of UTRA TDD ad hoc and IEEE 802.11b in Vehicular Environments. In *Proc. 57th IEEE Semiannual Vehicular Technology Conference*, Jeju, South Korea, April 2003.

[EWER03] Wilfried Enkelmann, Lars Wischhof, André Ebner, and Hermann Rohling. FleetNet – Anwendungen für mobile Ad-hoc Netzwerke. *Praxis der Informationsverarbeitung und Kommunikation*, 26(4):197 – 202, October 2003. (in German).

[EWR04] André Ebner, Lars Wischhof, and Hermann Rohling. Aspects of Decentralized Time Synchronization in Vehicular Ad hoc Networks. In *Proc. 1st International Workshop on Intelligent Transportation (WIT 2004)*, pages 67–72, Hamburg, Germany, March 2004.

[EWR+05] André Ebner, Lars Wischhof, Hermann Rohling, Rüdiger Halfmann, and Matthias Lott. Time Synchronization in Highly Dynamic Ad Hoc Networks. In Walter Franz, Hannes Hartenstein, and Martin Mauve, editors, *Inter-Vehicle Communications Based on Ad Hoc Networking Principles – The FleetNet Project*, chapter 1, pages 1–27. Universitätsverlag Karlsruhe, June 2005.

[Fal99] Kevin Fall. Network Emulation in the Vint/NS Simulator. In *Proc. IEEE Symposium on Computers and Communications (ISCC99)*, Red Sea, Egypt, July 1999.

[Fal03] Kevin Fall. A Delay-Tolerant Network Architecture for Challenged Internets. In *Proc. 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM '03)*, pages 27–34, New York, NY, USA, 2003. ACM Press.

[Fre04] Hannes Frey. Scalable Geographic Routing Algorithms for Wireless Ad Hoc Networks. *IEEE Network*, 18(4):18–22, July 2004.

[fSI03a] International Organization for Standardization (ISO). Road Vehicles – Controller Area Network (CAN) – Part 1: Data link layer and physical signalling. ISO Standard 11898-1, 2003.

[fSI03b] International Organization for Standardization (ISO). Road Vehicles – Controller Area Network (CAN) – Part 2: High-speed medium access unit. ISO Standard 11898-2, 2003.

[fSI04] International Organization for Standardization (ISO). Road Vehicles – Controller Area Network (CAN) – Part 3: Low-speed, fault-tolerant, medium dependent interface. ISO Standard 11898-3, 2004.

[FTMT+05] Holger Füßler, Marc Torrent-Moreno, Matthias Transier, Andreas Festag, and Hannes Hartenstein. Thoughts on a Protocol Architecture for Vehicular Ad-hoc Networks. In *Proc. Second International Workshop on Intelligent Transportation (WIT 2005)*, March 2005.

[FWK+03] Holger Füßler, Jörg Widmger, Michael Käsemann, Martin Mauve, and Hannes Hartenstein. Contention-Based Forwarding for Mobile Ad-Hoc Networks. *Elsevier's Ad-Hoc Networks*, 1(4):351–369, November 2003.

[GG05] Yvonne Günter and Hans Peter Großmann. Usage of Wireless LAN for Inter-Vehicle Communication. In *Proc. 8th International IEEE Conference on Intelligent Transportation Systems*, pages 296–301, Vienna, Austria, September 2005.

[GGHL05] Arpita Ghosh, Dan Greene, Qingfeng Huang, and Juan Liu. Variable-Resolution Information Dissemination. In *Proc. Second Annual IEEE Communication Society Conference on Sensor and Ad Hoc Communications and Networks (SECON 2005)*, Santa Clara, California, USA, September 2005.

[GIO04] Samir Goel, Tomasz Imielinski, and Kaan Ozbay. Ascertaining the Viability of WiFi based Vehicle-to-Vehicle Network for Traffic Information Dissemination. In *Proc. 7th Annual IEEE Intelligent Transportation Systems Conference (ITSC)*, October 2004.

[GK00] Piyush Gupta and P. R. Kumar. The Capacity of Wireless Networks. *IEEE Transactions on Information Theory*, IT-46(2):388–404, March 2000.

[GMRL05] Martin Grade, Klaus Meier, Bernd Rech, and Andreas Lübke. Physical IEEE 802.11-Measurements in Automotive Environment. In *Proc. 5th European Congress and Exhibition on Intelligent Transport Systems and Services*, Hannover, Germany, July 2005.

[GNB01] Xia Gao, Thyagarajan Nandagopal, and Vaduvur Bharghavan. Achieving Application Level Fairness Through Utility-Based Wireless Fair Scheduling. In *Proc. IEEE Global Telecommunications Conference (GLOBECOM 2001)*, pages 3257 – 3261, November 2001.

[GT92] Nathan Gartner (Editor) and TRB Committee A3A11. Traffic Flow Theory: A State-of-the-Art Report. Technical Report Update of TRB Special Report 165, Transportation Research Board (TRB) and Oak Ridge National Laboratory (ORNL), June 1992.

[GT02] Matthias Grossglauser and D. Tse. Mobility Increases the Capacity of Ad Hoc Wireless Networks. *IEEE/ACM Transactions on Networking*, 10(4):477–486, August 2002.

[Hal88] Peter Hall. *Introduction to the Theory of Coverage Processes*. Wiley Series in Probability and Mathematical Statistics. Wiley and Sons, New York, November 1988.

[Har00] Ingo Harre. AIS Adding New Quality to VTS Systems. *Journal of Navigation*, 53(3):527–539, September 2000. The Royal Institute of Navigation, Cambridge University Press.

[HB01] Serge P. Hoogendoorn and Piet H.L. Bovy. State-of-the-art of Vehicular Traffic Flow Modelling. *Journal of Systems and Control Engineering*, 215(4):283–304, August 2001. Special Issue on Road Traffic Modelling and Control.

[HBBW04] Marc Heissenbüttel, Torsten Braun, Thomas Bernoulli, and Markus Wälchli. BLR: Beacon-Less Routing Algorithm for Mobile Ad Hoc Networks. *Elsevier's Computer Communications Journal*, 27(11):1076–1086, July 2004.

[HBL+01] Hannes Hartenstein, Bernd Bochow, Matthias Lott, André Ebner, M. Radimirsch, and D. Vollmer. Position-Aware Ad Hoc Wireless Networks for Inter-Vehicle Communications: the Fleetnet Project. In *Proc. ACM Symposium on Mobile Ad Hoc Networking & Computing, MobiHoc 2001*, Long Beach, California, USA, October 2001.

[HBWP04] Philipp Hofmann, Christian Bettstetter, Jeremie Wehren, and Christian Prehofer. Performance Impact of Mobility in an Emulated IP-based Multihop Radio Access Network. In *Proc. IEEE/IFIP Intern. Conf. on Mobile and Wireless Communication Networks (MWCN)*, Paris, France, October 2004.

[Hel01] Dirk Helbing. Traffic and Related Self-Driven Many-Particle Systems. *Reviews of Modern Physics*, 73(4):1067–1141, October 2001.

[HM05] Simon Haykin and Michael Moher. *Modern Wireless Communications*. Pearson Prentice Hall, 2005.

[ian] Internet Assigned Numbers Authority (IANA). http://www.iana.org.

[IEE] IEEE 802.11p Std. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications – Amendment (under discussion): Wireless Access in Vehicular Environments. Active Project Autorization Request – Task Group P.

[IEE99a] IEEE 802.11 Std. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 1999. Also adopted as ISO/IEC 8802-11: 1999.

[IEE99b] IEEE 802.11a Std. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications – Amendment 1: High-speed Physical Layer in the 5 GHz band, 1999. Also adopted as ISO/IEC 8802-11:1999/Amd 1:2000(E).

[JPS01] Rahul Jain, Anuj Puri, and Raja Sengupta. Geographical Routing using Partial Information for Wireless Ad Hoc Networks. *IEEE Personal Communications Magazine*, 8(1):48–57, February 2001.

[JS04] Glenn Judd and Peter Steenkiste. Repeatable and Realistic Wireless Experimentation through Physical Emulation. *SIGCOMM Comput. Commun. Rev.*, 34(1):63–68, 2004.

[KEOO04] Gökhan Korkmaz, Eylem Ekici, Füsun Özgüner, and Ümit Özgüner. Urban Multi-hop Broadcast Protocol for Inter-Vehicle Communication

Systems. In *Proc. First ACM Workshop on Vehicular Ad Hoc Networks*, pages 76–85. ACM Press, 2004.

[Kho05] Chonlatee Khorakhun. Comparison of Routing and Data Dissemination Protocols in Vehicular Ad Hoc Networks. Master's thesis, Hamburg University of Technology, Hamburg, Germany, February 2005.

[KM99] Dietmar Kopitz and Bev Marks. Traffic and Travel Information Broadcasting – Protocols for the 21st Century. *EBU Technical Review*, 1(279):4–12, 1999.

[KMJ00] Qifa Ke, D. Maltz, and D. Johnson. Emulation of Multi-Hop Wireless Ad Hoc Networks. In *Proc. 7th International Workshop on Mobile Multimedia Communications (MoMuC2000)*, October 2000.

[Kra88] Stefan Krauß. Microscopic Modelling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics. Forschungsbericht DLR-FB–98-08, Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center), Köln, Germany, April 1988. ISSN 1434-8454.

[KSA02] Timo Kosch, Christian Schwingenschlögl, and Li Ai. Information Dissemination in Multihop Inter-Vehicle Networks – Adapting the Ad-hoc On-demand Distance Vector Routing Protocol (AODV). In *Proc. 5th IEEE International Conference on Intelligent Transportation Systems*, September 2002.

[Lee95] Kam Lee. Adaptive Network Support for Mobile Multimedia. In *Proc. ACM Mobicom 1995*, Berkeley, California, USA, November 1995.

[LEM+04] Matthias Lott, André Ebner, Michael Meincke, Rüdiger Halfmann, Lars Wischhof, Egon Schulz, and Hermann Rohling. An Air-Interface for Ad hoc Networks Supporting High Mobility. *Journal of Communications and Networks*, 6(4):295–306, December 2004.

[LH04] Jun Luo and Jean-Pierre Hubaux. A Survey of Inter-Vehicle Communication. Technical Report IC/2004/24, School of Computer and Communication Sciences, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, March 2004.

[LHSR01] Matthias Lott, Rüdiger Halfmann, Egon Schulz, and Markus Radimirsch. Medium Access and Radio Resource Management for Ad hoc Networks based on UTRA TDD. In *Proc. ACM Symposium on Mobile Ad Hoc Networking & Computing (MobiHoc 2001)*, Long Beach, California, October 2001.

[LMCL01] Haiyun Luo, Paul Medvedev, Jerry Cheng, and Songwu Lu. A Self-Coordinating Approach to Distributed Fair Queueing in Ad Hoc Wireless Networks. In *Proc. IEEE Conference on Computer Communications (INFOCOM 2001)*, 2001.

[LMFH05] Christian Lochert, Martin Mauve, Holger Füßler, and Hannes Hartenstein. Geographic Routing in City Scenarios. *ACM SIGMOBILE Mobile Computing and Communications Review (MC2R)*, 9(1):69 – 72, January 2005.

[LMH04] Matthias Lott, Michael Meincke, and Rüdiger Halfmann. Exploitation of Multiple Frequency Channels in WLAN. In *Proc. 1st International Workshop on Intelligent Transportation (WIT 2004)*, pages 55–59, Hamburg, Germany, March 2004.

[LMT+04] Stefan Lorkowski, Peter Mieth, Kai-Uwe Thiessenhusen, Dhiraj Chauhan, Bert Passfeld, and Ralf-Peter Schäfer. Towards Area-Wide Traffic Monitoring-Applications Derived from Probe Vehicle Data. In C. Sinha Kumares, T. F. Fwa, L. Cheu Ruey, and Lee Der-Horng, editors, *Proc. 8th International Conference on Applications of Advanced Technologies in Transportation Engineering*, pages 389 – 394, Beijing, China, May 2004. ASCE.

[LMZ+06] Uichin Lee, Eugenio Magistretti, Biao Zhou, Mario Gerla, Paolo Bellavista, and Antonio Corradi. Efficient Data Harvesting in Mobile Sensor Platforms. In *Proc. Second IEEE International Workshop on Sensor Networks and Systems for Pervasive Computing (PerSeNS 2006)*, Pisa, Italy, March 2006.

[LÖ05] Yiting Liu and Ümit Özgüner. Quantitative Evaluation of Inter-Vehicle Communication Effect in Highway Transportation from Micro and

Macro Views. *Int. J. Vehicle Information and Communication Systems*, 1(1/2):152–180, 2005.

[Lüb04] Andreas Lübke. Car-to-Car Communication – Technologische Herausforderungen. In *Fachtagungsbericht GMM, VDE-Kongress 2004*, Berlin, Germany, October 2004. VDE, VDE-Verlag. (in German).

[Mau05] Jürgen Maurer. *Strahlenoptisches Kanalmodell für die Fahrzeug-Fahrzeug-Funkkommunikation*. PhD thesis, Institut für Höchstfrequenztechnik und Elektronik (IHE), Universität Karlsruhe, Karlsruhe, Germany, 2005. (in German).

[Mic01] Lachlan B. Michael. Adaptive Layered Data Structure for Inter-vehicle Communication in Ad-hoc Networks. In *Proc. 8th World Congress on Intelligent Transportation Systems (ITS 2001)*, Sydney, Australia, October 2001.

[MJK+00] Robert Morris, John Jannotti, Frans Kaashoek, Jinyang Li, and Douglas Decouto. CarNet: A Scalable Ad Hoc Wireless Network System. In *Proc. 9th ACM SIGOPS European workshop*, Kolding, Denmark, September 2000.

[MKO00] Satoshi Matsuda, Hiroyuki Koike, and Hiromi Okada. Vehicular Information BROadcasting Relay (VIBROR) Protocol for Inter-Vehicle Communications. In *Proc. IEEE Semiannual Vehicular Technology Conference (VTC Fall)*, pages 2005–2010, Boston, USA, September 2000.

[MMe04] C. Siva Ram Murthy, B. S. Manoj, and Theodore S. Rappaport (editor). *Ad Hoc Wireless Networks: Architectures and Protocols*. Prentice Hall Professional Technical Reference, Upper Saddle River, New Jersey, 2004.

[MUM03] Koshiro Mitsuya, Keisuke Uehara, and Jun Murai. The In-vehicle Router System to support Network Mobility. In *Proc. International Conference on Information Networking (ICOIN) 2003*, Jeju Island, Korea, February 2003.

[NBG06] Valery Naumov, Rainer Baumann, and Thomas Gross. An Evaluation of Inter-Vehicle Ad Hoc Networks based on Realistic Vehicular Traces.

In *Proc. ACM Symposium on Mobile Ad Hoc Networking & Computing, MobiHoc 2006*, pages 108–119, Florence, Italy, May 2006. ACM Press.

[NDP+05] Alok Nandan, Shirshanka Das, Giovanni Pau, M.Y. Sanadidi, and Mario Gerla. Cooperative Downloading in Vehicular Ad Hoc Networks. In *Proc. Second Annual Conference on Wireless On demand Network Systems and Services (WONS 2005)*, St Moritz, Switzerland, 2005.

[NDZ+05] Alok Nandan, Shirshanka Das, Biao Zhou, Giovanni Pau, and Mario Gerla. AdTorrent: Digital Billboards for Vehicular Networks. In *Proc. Vehicle-to-Vehicle Communication Workshop (V2VCOM 2005)*, San Diego, USA, June 2005.

[Neu00] Lutz Neubert. *Statistische Analyse von Verkehrsdaten und die Modellierung von Verkehrsfluss mittels zellularer Automaten*. PhD thesis, Gerhard-Mercator-Universität Duisburg, Duisburg, Germany, May 2000. (in German).

[NS92] Kai Nagel and Michael Schreckenberg. A Cellular Automaton Model for Freeway Traffic. *J. Phys. I (France)*, 1992(2):2221–2229, 1992.

[NTDW03] Eric Nettleton, Sebastian Thrun, and Hugh Durrant-Whyte. Decentralised SLAM with Low-Bandwidth Communication for Teams of Airborne Vehicles. In *Proc. International Conference on Field and Service Robotics*, Lake Yamanaka, Japan, 2003.

[NWWS97] Kai Nagel, Dietrich E. Wolf, Peter Wagner, and Patrice Simon. Two-Lane Traffic Rules for Cellular Automata: A Systematic Approach. Technical Report LA-UR 97-4706, Los Alamos National Laboratory, Los Alamos, NM, USA, 1997.

[NZ03] Lionel M. Ni and Pei Zheng. EMPOWER: A Network Emulator for Wireline and Wireless Networks. In *Proc. 22nd Annual Joint Conference of the IEEE Computer and Communications Societies (InfoCom 2003)*, San Francisco, USA, April 2003.

[OK04] Jörg Ott and Dirk Kutscher. Drive-thru Internet: IEEE 802.11b for Automobile Users. In *Proc. IEEE Infocom 2004 Conference*, 2004.

[Pap91] Athanasios Papoulis. *Probability, Random Variables and Stochastic Processes*. McGraw-Hill series in electrical engineering : Communications and signal processing. McGraw-Hill, New York, 3rd edition, 1991.

[PHC$^+$03] Andreas Pottmeier, Sigurdur F. Hafstein, Roland Chrobok, Joachim Wahle, and Michael Schreckenberg. The Traffic State of the Autobahn Network of North Rhine-Westphalia: An Online Traffic Simulation. In *Proc. 10th World Congress and Exhibition on Intelligent Transport Systems and Services*, Madrid, Spain, 2003.

[PNS00] Ratish J. Punnoose, Pavel V. Nikitin, and Daniel D. Stancil. Efficient Simulation of Ricean Fading within a Packet Simulator. In *Proc. 52nd IEEE Semiannual Vehicular Technology Conference*, volume 2, pages 764–767, Boston, MA, USA, September 2000.

[Pro01] John G. Proakis. *Digital Communications*. McGraw-Hill, 4th edition, 2001.

[Rap01] Theodore S. Rappaport. *Wireless Communications: Principles and Practice*. Prentice Hall, 2nd edition, December 2001.

[Ras01] Kai Rascher. *Untersuchungen zum Kanalzugriff in selbstorganisierenden Datenfunknetzen*. PhD thesis, Braunschweig Carolo-Wilhelmina University of Technology, Braunschweig, Germany, 2001. (in German).

[RB04] Bozidar Radunovic and Jean-Yves Le Boudec. Performance Objectives of Multihop Wireless Networks. *IEEE Transactions on Mobile Computing*, 3(4):334 – 349, October 2004.

[RH05] Maxim Raya and Jean-Pierre Hubaux. The Security of Vehicular Ad Hoc Networks. In *Proc. 3rd ACM Workshop on Security of Ad Hoc and Sensor Networks (SASN '05)*, pages 11–21, New York, NY, USA, 2005. ACM Press.

[RMJ03] Michael Rudack, Michael Meincke, and Klaus Jobmann. On Traffic Dynamical Aspects of Inter Vehicle Communications (IVC). In *Proc. 57th IEEE Semiannual Vehicular Technology Conference (VTC Fall)*, Orlando, Florida, USA, October 2003.

[RRR05] Hans-J. Reumerman, Marco Roggero, and Marco Ruffini. The Application-Based Clustering Concept and Requirements for Intervehicle Networks. *IEEE Communications Magazine*, 43(4):108–113, April 2005.

[SBSC02] Jatinder Pal Singh, Nicholas Bambos, Bhaskar Srinivasan, and Detlef Clawin. Wireless LAN Performance Under Varied Stress Conditions in Vehicular Traffic Scenarios. In *Proc. IEEE 56th Vehicular Technology Conference*, Vancouver, Canada, September 2002.

[Sch05] Christian Schwingenschlögl. *A Framework for Secure and Efficient Communication in Mobile Ad Hoc Networks*. PhD thesis, Technische Universität München, München, Germany, June 2005.

[SG85] Rajeev Sinha and S.C. Gupta. Mobile Packet Radio Networks: State-of-the-Art. *IEEE Communications Magazine*, 23(3):53–61, March 1985.

[SJ04] Amit Kumar Saha and David B. Johnson. Modeling Mobility for Vehicular Ad Hoc Networks. In *Proc. First ACM Workshop on Vehicular Ad Hoc Networks (VANET 2004)*. ACM Press, 2004.

[SMM$^+$05] Will Specks, Kirsten Matheus, Rolf Morich, Ingrid Paulus, Cornelius Menig, Andreas Lübke, and Bernd Rech. Car-to-Car Communication – Market Introduction and Success Factors. In *Proc. 5th European Congress and Exhibition on Intelligent Transport Systems and Services*, Hannover, Germany, July 2005.

[SRC84] Jerome H. Saltzer, David P. Reed, and David D. Clark. End-to-End Arguments in System Design. *ACM Transactions on Computer Systems*, 2(4):277–288, November 1984.

[SRJB03] Rahul C. Shah, Sumit Roy, Sushant Jain, and Waylon Brunette. Data MULEs: Modeling and Analysis of a Three-Tier Architecture for Sparse Sensor Networks. *Elsevier Ad Hoc Networks Journal*, 1(2-3):215–233, September 2003.

[SS93] Andreas Schadschneider and Michael Schreckenberg. Cellular Automaton Models and Traffic Flow. *Journal of Physics A: Mathematical and General*, 1993(26):679–683, 1993.

[SX04] Raja Sengupta and Qing Xu. DSRC for Safety Systems. *Intellimotion – California PATH's Quarterly Newsletter*, 10(4):2–11, 2004.

[SYYK06] Weihua Sun, Hirozumi Yamaguchi, Koji Yukimasa, and Shinju Kusumoto. GVGrid: A QoS Routing Protocol for Vehicular Ad Hoc Networks. In *Proc. Fourteenth IEEE International Workshop on Quality of Service (IWQoS 2006)*, pages 130–139, New Haven, CT, USA, June 2006.

[Tan88] Andrew S. Tanenbaum. *Computer Networks*. Prentice-Hall International, 2nd edition, 1988.

[TC03] Jing Tian and Luca Coletti. Routing Approach in CarTALK 2000 Project. In *Proc. IST Mobile and Wireless Communications Summit 2003*, volume 2, pages 473–477, Aveiro, Portugal, June 2003.

[TJM+04] Vikas Taliwal, Daniel Jiang, Heiko Mangold, Chi Chen, and Raja Sengupta. Empirical determination of channel characteristics for DSRC vehicle-to-vehicle communication. In *VANET '04: Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks*, pages 88–88, New York, NY, USA, 2004. ACM Press.

[TMJH04] Marc Torrent-Moreno, Daniel Jiang, and Hannes Hartenstein. Broadcast Reception Rates and Effects of Priority Access in 802.11-based Vehicular Ad-Hoc Networks. In *Proc. 1st ACM Workshop on Vehicular Ad Hoc Networks (VANET 2004)*, pages 10–18. ACM Press, 2004.

[TMSH05] Marc Torrent-Moreno, Paolo Santi, and Hannes Hartenstein. Fair Sharing of Bandwidth in VANETs. In *Proc. Second ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2005)*, Cologne, Germany, September 2005.

[TvS02] Andrew S. Tanenbaum and Maarten van Steen. *Distributed Systems: Principles and Paradigms*. Prentice Hall, 1 edition, 2002.

[UTHO05] Jumpei Ueki, Sentarou Tasaka, Yuji Hatta, and Hiromi Okada. Vehicular-Collision Avoidance Support System (VCASS) by Inter-Vehicle Communications for Advanced ITS. *IEICE Trans. Fundamentals of Electronics, Communications and Computer Sciences*, E88-A(7):1816–1823, July 2005.

[Var04] Upkar Varshney. Vehicular Mobile Commerce. *IEEE Computer*, 37(12):116–118, December 2004.

[VB00] Amin Vahdat and David Becker. Epidemic Routing for Partially-Connected Networks. Technical Report CS-2000-06, Duke Univ., 2000.

[Ver97] R. Verdone. Multi-hop R-Aloha for inter-vehicle communication at millimeter waves. *IEEE Transactions on Vehicular Technology*, 46(4):992–1005, November 1997.

[Vol] Volkswagen AG. Low-Level CAN Framework (LLCF). `http://www.llcf.de`, retrieved March 1, 2006.

[WER+03a] Lars Wischhof, André Ebner, Hermann Rohling, Matthias Lott, and Rüdiger Halfmann. Adaptive Broadcast for Travel and Traffic Information Distribution Based on Inter-Vehicle Communication. In *Proc. IEEE Intelligent Vehicles Symposium (IV 2003)*, Columbus, Ohio, USA, June 2003.

[WER+03b] Lars Wischhof, André Ebner, Hermann Rohling, Matthias Lott, and Rüdiger Halfmann. SOTIS – A Self-Organizing Traffic Information System. In *Proc. 57th IEEE Semiannual Vehicular Technology Conference*, volume 4, pages 2442–2446, Jeju, South Korea, April 2003. ISSN: 1090-3038.

[WER04] Lars Wischhof, André Ebner, and Hermann Rohling. Self-Organizing Traffic Information System based on Car-to-Car Communication: Prototype Implementation. In *Proc. 1st International Workshop on Intelligent Transportation (WIT 2004)*, pages 49–53, Hamburg, Germany, March 2004.

[WER05a] Lars Wischhof, André Ebner, and Hermann Rohling. Information Dissemination in Self-Organizing Intervehicle Networks. *IEEE Transactions on Intelligent Transportation Systems*, 6(1):90–101, March 2005.

[WER+05b] Lars Wischhof, André Ebner, Hermann Rohling, Matthias Lott, and Rüdiger Halfmann. Self-Organizing Traffic Information System (SOTIS). In Walter Franz, Hannes Hartenstein, and Martin Mauve, editors, *Inter-Vehicle Communications Based on Ad Hoc Networking Principles – The FleetNet Project*, chapter 8, pages 233–258. Universitätsverlag Karlsruhe, June 2005.

[WER06] Lars Wischhof, André Ebner, and Hermann Rohling. Self-Generated Road Status Maps based on Vehicular Ad Hoc Communication. In *Proc. 3rd International Workshop on Intelligent Transportation (WIT 2006)*, pages 217–222, Hamburg, Germany, March 2006.

[WFGH04] Hao Wu, Richard Fujimoto, Randall Guensler, and Michael Hunter. MDDV: a Mobility-Centric Data Dissemination Algorithm for Vehicular Networks. In *Proc. 1st ACM Workshop on Vehicular Ad Hoc Networks (VANET 2004)*, pages 47–56. ACM Press, 2004.

[WFR04] Hao Wu, Richard Fujimoto, and George Riley. Analytical Models for Data Dissemination in Vehicle-to-Vehicle Networks. In *Proc. IEEE Vehicular Technology Conference 2004-Fall*, Los Angeles, CA, USA, September 2004.

[WR05a] Lars Wischhof and Hermann Rohling. Congestion Control in Vehicular Ad Hoc Networks. In *Proc. IEEE International Conference on Vehicular Electronics and Safety 2005 (ICVES 2005)*, pages 58–63, Xi'an, Shaanxi, China, October 2005.

[WR05b] Lars Wischhof and Hermann Rohling. On Utility-Fair Broadcast in Vehicular Ad Hoc Networks. In *Proc. 2nd International Workshop on Intelligent Transportation (WIT 2005)*, pages 47–51, Hamburg, Germany, March 2005.

[XB04] Huaying Xu and Matthew Barth. A Transmission-Interval and Power-Level Modulation Methodology for Optimizing Inter-Vehicle Communications. In *Proc. First ACM Workshop on Vehicular Ad Hoc Networks (VANET 2004)*, pages 97–98. ACM Press, 2004.

[XMS04] Qing Xu, Tony Mak, and Raja Sengupta. Vehicle-to-Vehicle Safety Messaging in DSRC. In *Proc. 1st ACM Workshop on Vehicular Ad Hoc Networks (VANET 2004)*, Philadelphia, PA, USA, October 2004.

[XOW04] Bo Xu, Aris Ouksel, and Ouri Wolfson. Opportunistic Resource Exchange in Inter-Vehicle Ad-Hoc Networks. In *Proc. IEEE International Conference on Mobile Data Management (MDM'04)*, pages 4–13, Berkeley, California, USA, January 2004.

[XS01] Shugong Xu and Tarek Saadawi. Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks? *IEEE Communications Magazine*, 39(6):130–137, June 2001.

[YEY+04] JiJun Yin, Tamer ElBatt, Gavin Yeung, Bo Ryu, Stephen Habermas, Hariharan Krishnan, and Timothy Talty. Performance Evaluation of Safety Applications over DSRC Vehicular Ad Hoc Networks. In *Proc. 1st ACM Workshop on Vehicular Ad Hoc Networks (VANET 2004)*, October 2004.

[YR05] Xu Yang and Will Recker. Simulation Studies of Information Propagation in a Self-organizing Distributed Traffic Information System. ATMS Testbed Technical Report TTR3-09, Institute of Transportation Studies, University of California Irvine, June 2005.

[YV05] Xue Yang and Nitin H. Vaidya. On the Physical Carrier Sense in Wireless Ad Hoc Networks. In *Proc. IEEE INFOCOM 2005*, Miamy, Florida, USA, March 2005.

[ZR03] Jing Zhu and Sumit Roy. MAC for Dedicated Short Range Communications in Intelligent Transport System. *IEEE Communications Magazine*, 41(12):60–67, December 2003.

[ZS03] A. D. Zeitlin and R. C. Strain. Augmenting ADS-B with Traffic Information Service-Broadcast. *IEEE Aerospace and Electronics Systems Magazine*, 18(10):13–18, October 2003. ISSN: 0885-8985.

[ZSO+05] Yunpeng Zang, Lothar Stibor, Georgios Orfanos, Shumin Guo, and Hans-Jürgen Reumerman. An Error Model for Inter-Vehicle Communications in Highway Scenarios at 5.9 GHz. In *Proc. Second ACM International Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks*, pages 49–56, Montreal, Quebec, Cannada, October 2005.

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