Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Institut für
Technische Informatik und
Kommunikationsnetze

Performance Enhancement of an Intersection Assistance System by Integrating WLAN Ad-Hoc Network with Multi-Hop Capabilities

Niklaus Frey

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Tutors:
Dr. Felix Klanner (BMW Group Research and Technology)
Dr. Peter Zahn (BMW Group Research and Technology)
Dr. Thrasyvoulos Spyropoulos (ETH Zürich, CSG)

Supervisor: Prof. Dr. Bernhard Plattner

BMW Group
Research and Technology

Abstract

The goal of this master thesis is the development of an ad-hoc multi-hop protocol based on car-to-car communication to enhance the performance of an existing intersection assistance system in terms of message dissemination. Currently a single-hop protocol is used which does not allow for a successful data exchange between approaching vehicles on intersections with line of sight obstructions. By applying the multi-hop paradigm an improved functionality of the assistance system should be provided on intersections with line of sight obstructions. The evaluation of the developed protocol is performed both in a simulation environment and in a real road traffic scenario and it demonstrates the successful performance enhancement of the intersection assistance system.

Kurzfassung

Ziel dieser Masterarbeit ist die Entwicklung eines Ad-hoc Multi-Hop Protokolls für die Fahrzeug-Fahrzeug-Kommunikation, um die Leistung eines existierenden Kreuzungsassistenzsystems in Bezug auf die Kommunikationsabdeckung zu erhöhen. Aktuell wird ein Single-Hop Protokoll verwendet, welches an Kreuzungen mit einer Sichtverdeckung zwischen sich annähernden Fahrzeugen keinen Datenaustausch zwischen den Fahrzeugen zulässt. Durch Anwendung des Multi-Hop Ansatzes soll die Funktionalität des Assistenzsystems auch auf Kreuzungen mit einer Sichtverdeckung gewährleistet werden. Der Test des entwickelten Protokolls wird sowohl in einer Simulationsumgebung als auch im realen Strassenvekehr durchgeführt und zeigt, dass das Ziel der Leistungssteigerung des Kreuzungassistenzsystems erreicht wird.

Contents

1 Introduction 1
1.1 Motivation . . . 1
1.2 Problem Statement . . . 2
1.3 Outline . . . 3

2 State of the Art 5
2.1 Communication-based Intersection Assistant . . . 5
2.2 ACUp Communication Framework . . . 6
2.3 VISSIM Traffic Simulation Program . . . 7
2.4 VANET Multi-Hop Algorithms . . . 8
2.5 Summary . . . 9

3 Multi-Hop Routing Protocol Description 11
3.1 Objective . . . 11
3.2 Prerequisites . . . 11
3.3 Approach . . . 12
3.4 Discussion . . . 15

4 Implementation 17
4.1 ACUp Framework Extensions . . . 17
4.1.1 Local Communication Interface . . . 17
4.1.2 Framework Interconnection . . . 17
4.1.3 Multi-Hop Routing Component . . . 18
4.2 Matlab/Simulink Models . . . 19
4.2.1 Send2ACUp Model . . . 19
4.2.2 KQA Model . . . 19
4.3 Discussion . . . 21

5 Functional Evaluation and First Real-World Experiments 23
5.1 VISSIM Simulation . . . 23
5.1.1 Intersection Scenarios . . . 23
5.1.2 KQA Performance . . . 24
5.1.3 Single-Hop vs. Multi-Hop Routing Performance . . . 25
5.2 Real-World Test . . . 28
5.2.1 Intersection Scenario . . . 29
5.2.2 KQA Performance . . . 29
5.3 Discussion . . . 30

6 Conclusion 31

7 Outlook 33

Acknowledgment 35

A Schedule and Work Progress 37

B Task Description 39

List of Abbreviations

ACUp	AKTIV Communication Unit with 802.11p
AKTIV	Adaptive und Kooperative Technologien für den Intelligenten Verkehr
API	Application Programming Interface
C2C-CC	CAR 2 CAR Communication Consortium
CAN	Controller Area Network
Car2X	Car to Anything Communication
CoCar	Cooperative Cars
DSRC	Dedicated Short Range Communications
GPS	Global Positioning System
HSPA	High Speed Packet Access
IEEE	Institute of Electrical and Electronics Engineers
KQA	Kommunikationsbasierter Querverkehrsassistent
LAN	Local Area Network
LTE	Long Term Evolution
MAC	Media Access Control
MOM	Message Oriented Middleware
OSI	Open Systems Interconnection
PReVENT	Preventive and Active Safety Applications
RSU	Roadside Unit
SIM-TD	Sichere Intelligente Mobilität - Testfeld Deutschland
STL	Standard Template Library
TCP	Transmission Control Protocol
TTL	Time-to-Live
UMTS	Universal Mobile Telecommunications System
VANET	Vehicular Ad-Hoc Network
WAVE	Wireless Access in Vehicular Environments
WGS 84	World Geodetic System 1984
WSU	Wireless Safety Unit
XFace	Exchange Interface for Driving Environments

List of Figures

1.1 Single-Hop Communication 2
1.2 Multi-Hop Communication 2

2.1 Communication-based intersection assistant [32] 5
2.2 ACUp framework structure [33] 6
2.3 Simple intersection scenario in VISSIM 7

3.1 Multi-hop message flow 13
3.2 Queue routine run on intersection 14
3.3 Queue routine run in thread 15

4.1 Framework interconnection 18
4.2 Definition for the vehicle heading in VISSIM and for GPS systems 20
4.3 Intersection assistance system in the car 21
4.4 Intersection assistance system in the simulation 22

5.1 VISSIM intersection scenario 23
5.2 Average number of vehicles reached by each message 26
5.3 Average message latency 26
5.4 Total number of sent messages, no obstacles 27
5.5 Total number of sent messages, multi-hop routing protocol 28
5.6 Intersection used for the real-world evaluation 29

List of Tables

4.1 Send2ACUp variable list 20

5.1 Distance at which a warning is issued (radio range = 100m) 24
5.2 Distance at which a warning is issued (radio range = 200m) 25
5.3 Distance at which a warning is issued (radio range = 100m), RSU on the intersection 25
5.4 Distance from vehicle #1 to the center (multi-hop communication) 29
5.5 Distance from vehicle #1 to the center (single-hop communication) 30

A.1 Schedule 37

Chapter 1

Introduction

In the past few years, vehicular ad-hoc networks (VANETs) have become an important research field in the area of mobile ad-hoc networks. The main goal for developing VANETs is to allow an exchange of information relevant for passenger safety between the vehicles to assist the driver. Possible applications are for example early accident warnings, traffic light assistance or warnings about upcoming hazards on the road (e.g. ice or dense fog) [1]. Some of these applications could be realized based only on sensor technology in the own vehicle, but using communication to exchange information is often a more beneficial approach. It is easy for each vehicle to determine its own state and send this information to nearby vehicles, whereas sensing the whole surrounding to get the same information is substantially more complex or even impossible in some cases. In addition, the communication equipment is generally a lot cheaper than expensive sensor technology.

The communication partners in vehicular ad-hoc networks are on the one hand nearby vehicles (car-to-car communication) and on the other hand dedicated roadside equipment (car-to-infrastructure communication). The generic term *car-to-anything* (Car2X) is used to refer to the above two communication means.

Several projects around the world are currently running to achieve these goals. In the USA the *Vehicle Safety Communications Consortium* [2] is working on the *Dedicated Short Range Communications* (DSRC) [3] technology. In Japan, the effort is led by the *Internet ITS Consortium* [4] and in Europe several initiatives have been started such as the *CAR 2 CAR Communication Consortium* (C2C-CC) [5], the already completed *Preventive and Active Safety Applications* (PReVENT) project [6], the currently running *Adaptive and Cooperative Technologies for the Intelligent Traffic* (AKTIV) research initiative [7] or the just starting project *Sichere Intelligente Mobilität - Testfeld Deutschland* (Secure Intelligent Mobility - Test Area Germany) (SIM-TD) [8].

The background for this thesis is an intersection assistance application which is based on the VANET concepts. It has been developed to reduce the number of accidents at intersections by warning the driver about a potential yielding disregard.

1.1 Motivation

The intersection assistant currently uses the IEEE 802.11p draft wireless LAN standard [9] which operates in the 5.9GHz band. This draft standard allows for a dependable communication as long as the two communication partners are in range of each other and have a direct line of sight. The first criterion is mostly fulfilled in the intersection area whereas the second generally is not. In urban areas it is for example often the case that there is a line of sight obstruction in the relevant wavelength range (e.g. a building) situated at the corner of an intersection. This obstruction can inhibit the successful transmission of messages between two approaching vehicles as shown in Figure 1.1.

The motivation for this thesis is to ease exactly this problem by enhancing the communication with a multi-hop capable routing protocol. The idea is to exchange messages not only directly from one vehicle to another but to allow the relay of messages by other vehicles or infrastructure equipment. This greatly increases the chances of a possible communication between the approaching vehicles. Figure 1.2 illustrates the multi-hop solution for the same situation as depicted in Figure 1.1.

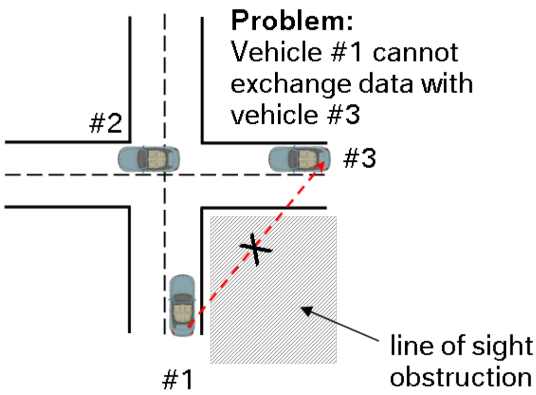

Figure 1.1: Single-Hop Communication

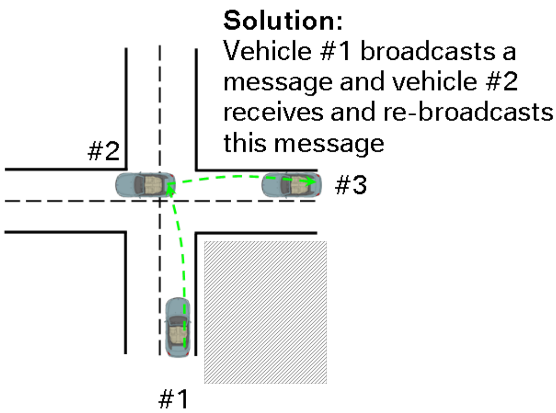

Figure 1.2: Multi-Hop Communication

1.2 Problem Statement

The goal of the thesis is to achieve a suitable multi-hop enhancement for the intersection assistance. The first step is to set up a simulation environment in which the whole system can be tested. The simulation is key to conduct a functional evaluation and prove the effectiveness of the multi-hop protocol before applying it in real world applications. The simulation environment utilizes the same components as the system used on the road, which allows for an easy integration of the multi-hop protocol in the vehicle. Another advantage of the simulation environment is the possibility to run different scenarios with several communicating vehicles coming from different directions. This is not yet possible in the real world because at the moment there is only a limited number of cars available that have the necessary communication equipment. This will change with the start of the SIM-TD project [8] where a larger test area with several hundred equipped vehicles will be available.
The second part consists of devising a suitable multi-hop algorithm specifically for the intersection application. To attain that goal, the current state of the art is studied and a multi-hop routing algorithm is drafted and implemented.
In the final step, a functional evaluation of the developed system is conducted. First, different scenarios in the simulation environment are analysed, followed by a real world test with three communicating vehicles on an intersection with a line of sight obstruction.

1.3 Outline

The rest of the thesis is structured as follows: Chapter 2 discusses the different components of the communication system and the simulation environment as well as the current state of the art of the research in the relevant ad-hoc network areas. In Chapter 3 the devised multi-hop routing algorithm is discussed. Details about the actual implementation of the routing algorithm as well as the components of the simulation environment are given in Chapter 4. The results of the simulation runs and the real world test are discussed in Chapter 5. Chapter 6 summarizes the findings of the thesis and provides a conclusion. An outlook on ideas to pursue in the future is outlined in Chapter 7.

Chapter 2

State of the Art

In this chapter the different components, namely the driver assistance system, the communication framework as well as the traffic simulation program are introduced. In a second part, related work in the relevant areas of vehicular ad-hoc networks is discussed.

2.1 Communication-based Intersection Assistant

The motivation for developing an intersection assistance system stems from traffic statistics, which show that the intersection area is an accident hot spot with a high number of bodily injuries. The goal of the intersection assistance system (KQA[1]), which has been developed at BMW Group Research and Technology, is to significantly reduce the number of these accidents. This is achieved by issuing a timely warning to the driver about potentially dangerous situations involving other vehicles in the intersection area.
Figure 2.1 illustrates the exemplary course of events for a car approaching an intersection on a give way path and a motorcycle driving on the right of way path.

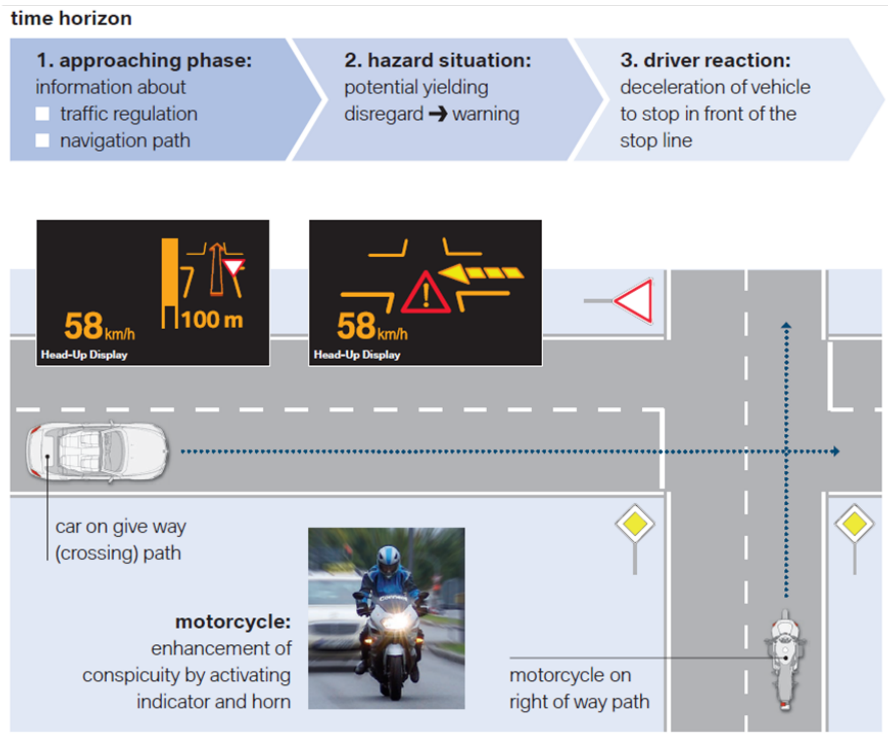

Figure 2.1: Communication-based intersection assistant [32]

[1] German abbreviation for: **K**ommunikationsbasierter **Q**uerverkehrs**a**ssistent

In the approaching phase, the driver of the car is informed at an early stage about the traffic regulation at the upcoming intersection along with the navigation path that should be taken. If the driver is assumed to be disregarding the give way sign, a warning with three components is emitted:

- A warning symbol is displayed in the the dashboard and the head-up display.
- An audible alarm is played.
- A haptic warning in the form of a deceleration with $3\frac{m}{s^2}$ is performed for 1 second.

Additionally, the motorcycle activates the indicator lights and the horn to enhance its conspicuity as shown in the picture at the bottom of Fig. 2.1. This should prompt the driver to evaluate the situation and react correspondingly to avoid a collision.
The assistance system is realized in Matlab/Simulink. It is running in specially equipped research vehicles with which its effectiveness and acceptance has been verified in various road tests [11]. To enable the communication between the vehicles, a wireless communication framework called ACUp is currently used which is further specified in the next section.

2.2 ACUp Communication Framework

The **A**KTIV **C**ommunication **U**nit with 802.11**p** (ACUp) [12] is a communication framework which has been developed as part of the German AKTIV research initiative [7]. It is based on the current development status of the European CAR 2 CAR Communication Consortium [5] which is a non-profit organisation initiated by the European vehicle manufacturers to create and establish an open European industry standard for Car2X applications.
The goal was to define an efficient, open and flexible communication system which

- utilizes the IEEE 802.11p draft wireless LAN standard (for an overview of the current draft, see [10])
- follows the current C2C-CC standards
- and offers an extensible architecture to allow for an easy extension and the integration of alternative components.

To achieve these goals, a modular C++ framework has been developed which follows a highly flexible plug-in approach with different layers and components which can easily be interchanged. The only drawback is that currently no comprehensive documentation for the framework is available which requires a thorough familiarization before new components can be integrated.
Figure 2.2 shows the basic structure of the ACUp framework which follows the standard OSI reference model.

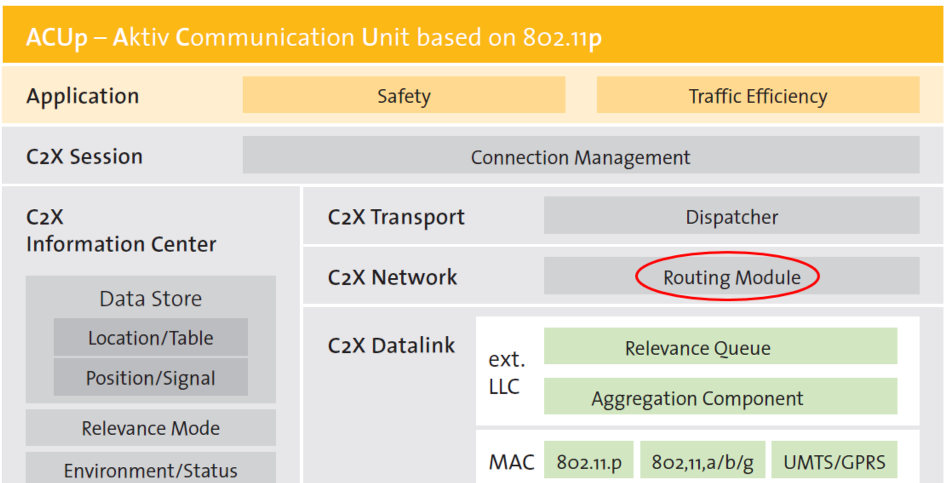

Figure 2.2: ACUp framework structure [33]

Although the framework is based on 802.11p as denoted in its name, several other communication standards can be implemented as indicated in the MAC layer (e.g. 802.11a/b/g, UMTS/GPRS). For this purpose new communication interfaces must be implemented which is feasible thanks to the flexible plug-in approach.
In addition to the standard OSI layers the ACUp framework includes an information center component in which certain data is gathered from the messages passing the framework. One feature which is implemented as part of the information center is a location table which stores the positions for all vehicles from which messages are received. This table could for example be used to implement a future geo-routing for the framework.
The multi-hop protocol, which is developed in this thesis, is implemented in the circled routing module of the network layer, which is currently just a reference implementation without any functionality. Several components which are not needed for the core functionality of the framework are only provided as a reference with no functionality. They simply pass all received messages from the lower layer to a higher one and vice versa. It will be the task of future work to develop and implement these components.
To interact with the client at the application layer, an API which follows the ideas of standard Message Oriented Middleware (MOM) is offered. Once a connection between the application and the communication framework is established and a session is created, messages that are passed to the framework will be processed in the different layers before they are sent out over the hardware communication interface.
To enable the interoperability of different versions of the ACUp framework, a basic message structure is defined for all versions. The basic structure can be extended by defining new message formats which are derived from the base class and therefore inherit the basic structure from it. This enables all versions of the framework to read and interpret a basic set of data.
The intersection assistance system discussed in the previous section is one example for a safety application using the ACUp framework. The traffic light assistant is another, which is also concerned with traffic efficiency by supporting the progressive signal system.

2.3 VISSIM Traffic Simulation Program

For the simulation of the traffic in the intersection area, a traffic simulation program called VISSIM has been used. It offers highly realistic traffic flow modelling and is well suited for the task at hand. Details about all the features that are available in VISSIM can be found in [13].
Figure 2.3 shows a screenshot of a relatively simple intersection scenario with two perpendicularly crossing streets carrying heavy traffic to illustrate the simulation view in VISSIM. There is no special traffic regulation and the usual priority to right rule is applied.

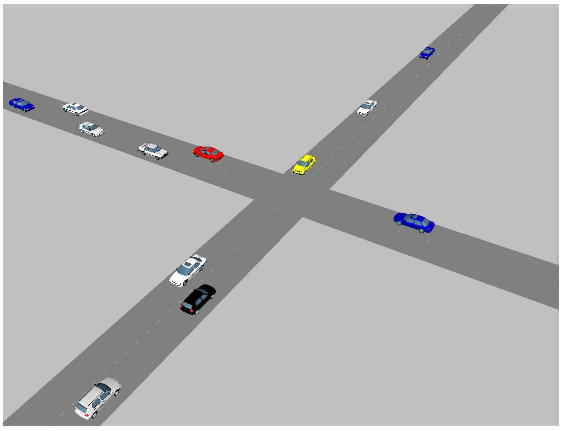

Figure 2.3: Simple intersection scenario in VISSIM

VISSIM is chosen because it offers the possibility to realistically simulate different traffic characteristics for various intersection scenarios. However, it does not allow accessing simulation data (e.g. position, orientation, speed of a vehicle) from another application. Since this data is needed as input for the intersection assistance system running in Matlab/Simulink, support for

a standard interface called XFace (eXchange interFACE for Driving Environments) had to be added. XFace is a C++ interface used to exchange car and environment data (e.g. for driving simulators).
PTV Vision, the manufacturer of VISSIM has added this support for XFace on behalf of BMW. A first version of the XFace addition has just been implemented into VISSIM by the start of the thesis. It has then been revised and enhanced in cooperation with PTV Vision during the development of the simulation environment. VISSIM now offers the required possibility to send information about the simulated vehicles to Simulink models via XFace.

2.4 VANET Multi-Hop Algorithms

Multi-hop algorithms are a hot topic in the VANET research community. In the following, a set of related work is discussed and their relevance for this thesis is identified.
An interesting combination of the idea of carry and forward with the predictability of vehicle mobility is presented in *VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks* [14]. The proposed protocols outperform existing solutions in terms of packet delivery ratio, data packet delay and traffic overhead but only under the assumption that street-level maps and traffic statistics are available. The authors of [15] additionally point out that the VADD routing protocol only works well with a high vehicle density but performs far from optimal for median to low densities. They propose a static-node assisted adaptive data dissemination protocol (SADV) to address this problem by storing packets in nodes installed at intersections and only forwarding them when necessary. Simulation results show that SADV outperforms VADD under low vehicle densities. As both protocols are intended for queries over very long distances, where delays up to minutes are tolerated, they are not suited for security applications like the intersection assistance system which requires very low latency in the range of 100ms [11].
In [16] a new multi-hop forwarding protocol is proposed as an extension to the IEEE 802.11 MAC layer. A method similar to that of a conventional MAC bridge is used. Two modes of forwarding are defined. If reachability information is available for the destination node an implicit unicast mode is used to select a single forwarding node. If no reachability information is available, the broadcast mode is used to inform all 1-hop neighbours to re-broadcast the received packet. The algorithm does not perform path discovery or maintenance which is a big advantage in the very dynamic vehicular ad-hoc networks, and it does not use position information. Although simulation revealed quite promising results, the proposed protocol cannot be used with the intersection assistance system. A change on the MAC layer of the 802.11 protocol would render the system incompatible with other communication partners not using this modified layer and therefore impede interoperability, which is a key requirement for the assistant. Only the approach of not performing path discovery or maintenance is followed up.
The safety application of hazard warning dissemination is studied in *A Vehicle-to-Vehicle Communication Protocol for Cooperative Collision Warning* [17] and in *Analysis of multi-hop emergency message propagation in vehicular ad hoc networks* [18]. The latter paper illustrates an interesting relation between the benefit of having a high single-hop reliability and the resulting multi-hop reliability. It states that a high single-hop reliability is only necessary if the vehicle density is low and that the relative benefits decrease with high car densities. It is thus desirable to have a density-aware message dissemination strategy. This finding is very interesting for the intersection assistance since the density of vehicles in the intersection area is varying substantially.
In *Local Density Estimation and Dynamic Transmission-Range Assignment in Vehicular Ad Hoc Networks* [19], a possibility for a vehicle to estimate its local traffic density without communication overhead is presented. The local density estimate is based on traffic-flow models which is a novel approach to predicting vehicle density that depends only on the vehicle's mobility pattern. The density estimate is then used by the DTRA algorithm to set the vehicle's transmission range. The devised protocol is transparent to communication protocols which allows it to be used in conjunction with existing protocols.
Both in *A Framework for Network Utility Maximization in VANETs* [20] and in *Strategies for Context-Adaptive Message Dissemination in Vehicular Ad Hoc Networks* [21] an approach for a communication system is presented which takes the individual network nodes' interest in information into account. This helps to distribute network resources as efficiently as possible

and to deliver information to where it is needed as fast as possible.
The paper entitled *Urban Multi-Hop Broadcast Protocol for Inter-Vehicle Communication Systems* [22] proposes an IEEE 802.11 based multi-hop broadcast protocol optimized for use in urban areas (UMB). The protocol fundamentally differentiates between *directional broadcasts* and *intersection broadcasts*. The goal of the *directional broadcast* is to select only the farthest node in range to forward and acknowledge a packet which leads to a very efficient message propagation. In addition, this vehicle selection works without any a priori knowledge of the network topology. The *intersection broadcast* is done by permanently installed repeaters which disseminate received packets into all continuative directions. It is shown by simulation that the devised protocol utilizes the channel very efficiently and allows for a high success percentage even at high packet loads and traffic densities. In a next step, the requirement of repeaters is eased by an alternative intersection broadcast protocol which is stated in [23]. The idea is to select the vehicle which is currently closest to the intersection to disseminate the packet instead of the repeater. This is done under the assumption that the closer a vehicle is to the intersection, the better coverage it has of the adjacent road segments. Simulation results show that the performance of this protocol is as good as the UMB protocol for intersections where the road segments are not blocked with obstacles. As the idea of using the vehicle closest to the intersection for message broadcast seems quite promising it has been adopted for this thesis, although realized in a different way, and will be further discussed in Section 3.3.

2.5 Summary

In this chapter, the already existing components of the communication-based intersection assistance system have been described along with the introduction of the traffic simulation program VISSIM. In Section 2.3 the XFace interface has been introduced which is an important part of the developed simulation environment that is further discussed in Chapter 4.
Some of the ideas presented in the related work section are picked up in the devised multi-hop algorithm described in detail in the following chapter.

Chapter 3

Multi-Hop Routing Protocol Description

This chapter illustrates the design of the multi-hop protocol which is developed to enhance the performance of the existing intersection assistance system. First, the objective and the prerequisites are discussed. Then a motivation for our approach is given followed by a detailed description.
The multi-hop protocol links with studies [20], [21] on minimizing the network utilization. In these two papers the relevance of a message is considered to set the priority with which a message is sent. Based on this work, the next step is to allow for a communication between two nodes over an intermediate node which is made possible by the devised multi-hop protocol.

3.1 Objective

The goal of the multi-hop protocol is to allow for a successful message exchange between vehicles in the intersection area even if they do not have a line of sight and/or are not in communication range, but are relevant to each other concerning the intersection assistance system. The latter case is often occurring on rural roads where vehicles are driving with higher speeds and therefore need to be warned earlier about a potential yielding disregard. This requires a successful communication over longer distances which is often not possible with single-hop communication. The first and possibly more critical case is line of sight obstruction. Especially in urban areas, there are many intersections with obstacles (e.g. hedges, buildings) which prohibit a direct communication between approaching vehicles on different branches of the intersection. Also moving obstacles such as a bus standing at a stop near the intersection could prohibit a successful single-hop communication and thereby a timely warning of the driver. In both cases the currently used single-hop system shows a poor communication performance. These deficiencies should be resolved by implementing a suitable multi-hop solution.

3.2 Prerequisites

The general conditions for the multi-hop routing protocol are set by the ACUp communication framework. The physical and the MAC layer are defined by the deployed 802.11p draft standard [9]. The upper layers, except for the application layer, are controlled by the ACUp framework where the multi-hop routing protocol resides as part of the network layer (cf. Figure 2.2).
All messages are broadcast to all nodes in the communication range and no confirmation in the form of an acknowledgment is sent back upon receipt.

3.3 Approach

The multi-hop protocol should be contributing to the goal of each vehicle receiving all relevant messages. Two vehicles are relevant for each other if they seem to arrive simultaneously at the same region of an intersection. It is important to generate as little extra load as possible but at the same time keep the latency of the message exchange low since messages arriving too late lose their relevance for the intersection assistance system.

The most obvious approach to ensure that all messages reach everyone would be to just flood the network with each message. This is not suitable though as already few vehicles would cause a substantial amount of data traffic by repeating a lot of redundant messages. An unnecessary congestion of the wireless medium would be the consequence of this overhead which results in high message latencies.

An optimal system would only generate additional traffic if the single-hop communication is not sufficient to ensure the message exchange and would then use an ideal path for the multi-hop communication. To get a performance near this optimum, the basic idea for the proposed multi-hop protocol is related to the concepts presented in [23] where only one node in communication range of the sender is selected to forward a packet. By picking just one vehicle to act as a relay and re-broadcast the message, there is only a minimal extra load. The challenge with this approach is to find a reliable way to identify the vehicle which is able to optimally disseminate the message in the intersection area so that it will reach all relevant nodes. To select the particular vehicle, a similar strategy as formulated in [23] is used, which appoints the vehicle that is currently closest to the intersection with the job of re-broadcasting the message. The method used to determine the closest vehicle to the center differs in the proposed protocol. In [23] a change to the MAC layer is proposed which is not feasible for the intersection assistance system which should guarantee the compatibility with the 802.11p draft standard.

One possible approach would be to use the location table storing the position of all surrounding vehicles and determine which vehicle should re-broadcast the message from that information. This pro-active approach does not lead to a satisfactory result though because the topology of the ad-hoc network is changing rapidly and the information in the location table is therefore outdated quickly. The approach also suffers from the problem that a vehicle needs to have received a broadcast message from all nearby vehicles to know their location. Additionally not all vehicles have the same location table, which makes selecting just one vehicle not feasible.

The approach which is employed in this thesis realizes a reactive routing protocol instead. The vehicle selection works without the a priori knowledge of the network topology. It differentiates between a vehicle receiving a message in the center of the intersection and a vehicle in the vicinity of the intersection. The reasoning for this differentiation is that a car right in the center of the intersection is in a near optimal position to broadcast a received message to all intersection branches and should therefore always be the first choice. If a car receives a message in the center of the intersection it re-broadcasts the message immediately. This can lead to messages being re-broadcast more than once if there is more than one vehicle in the center of the intersection but it is assumed that only a small number of cars are in the center at any point in time. If that is the case, the overhead should not be detrimental and the advantage is that every vehicle is able to re-broadcast received messages from an optimal position. Even cars passing the center of the intersection with a high speed in a very short amount of time will re-broadcast received messages. This would be difficult to achieve if a mechanism to determine whether there are other cars in the center was run before a message is re-broadcast.

In case no vehicle is in the center of the intersection, the goal is to pick the one which currently is closest to the center, similar to [23]. The assumption is that this car is most likely in the next best position to disseminate the message. To select the closest vehicle, a timer is set depending on the distance between the vehicle and the center when a message is received. If the vehicle does not receive another broadcast of the same message until the timer runs out the message is re-broadcast. Thus only the closest vehicle is expected to be re-broadcasting a message.

A basic requirement for the proposed algorithm is the knowledge of the own position in relation to the next intersection. Since this information is available in the assistance system it can be made available to the communication unit.

A flowchart of the resulting algorithm is given in Figure 3.1 which indicates how one of the three depicted paths is taken, depending on the current position of the vehicle receiving a message.

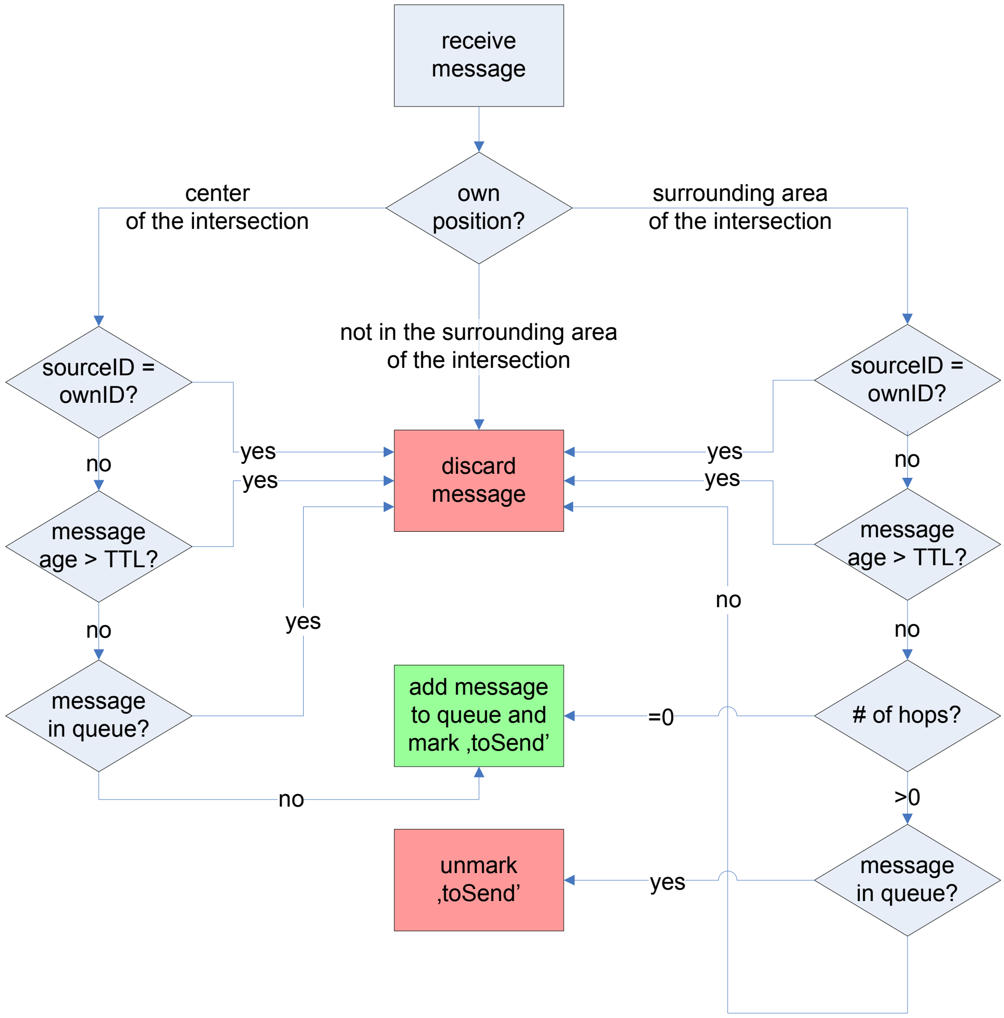

Figure 3.1: Multi-hop message flow

Center of the Intersection

If the vehicle is in the center of the intersection, which is defined as the intersecting area of the crossing streets, the received message is queued except if

- the source ID[1] is its own ID (the vehicle regularly sends updated messages and it is no use to repeat older messages)
- the time-to-live (TTL)[2] of the message is already expired
- the same message is already queued.

Afterwards, the routine shown in Figure 3.2 is executed to immediately broadcast all queued messages which have not been sent already.

[1] The temporarily assigned ID allows the identification of each vehicle. It is permuted over time so that no tracking is possible.

[2] The time-to-live is defined by the sending application as the timespan during which the contained information is relevant for other vehicles.

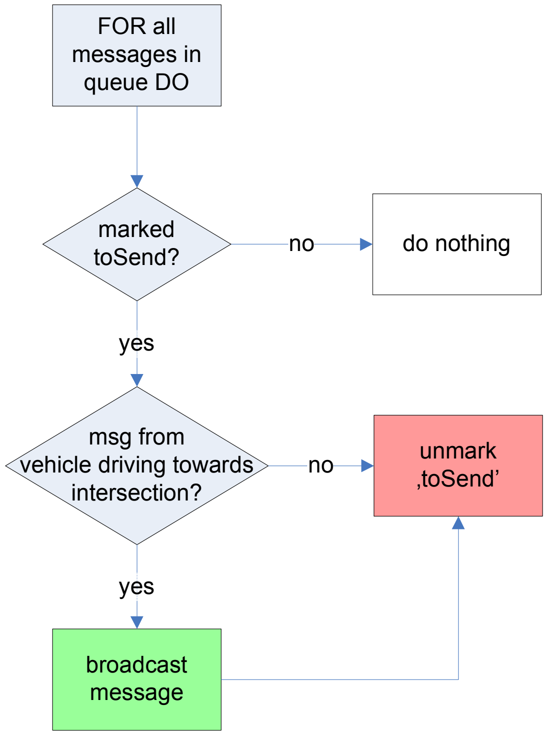

Figure 3.2: Queue routine run on intersection

An additional criterion, which is checked before the broadcast, is whether the vehicle which originally sent the message is driving towards the intersection; we will discuss this later. Vehicles driving away from the intersection pose no danger to approaching vehicles and their information does not need to be re-broadcast. This condition would have to be adapted if vehicles driving away from the intersection are in some way relevant for a future intersection assistance system.

Surrounding Area of the Intersection

If the vehicle receiving a message is not in the center but still in the vicinity of an intersection, the message is queued and a timer is set depending on the receiving vehicle's distance to the center of the intersection, except if

- the source ID is its own ID
- the time-to-live (TTL) of the message is already expired
- the message has already been re-broadcast.

If the message has already been re-broadcast at least once, it is checked if that same message exists in the queue already. If it does, this means that a vehicle closer to the intersection (whose timer has already run out) or a vehicle in the center of the intersection has sent it. The message does not have to be re-broadcast again and an according flag is set in the queue.
Figure 3.3 shows the routine which runs at a fixed interval (e.g. every 10ms) in a separate thread. The goal of this routine is different from the routine used for messages received in the center of the intersection as messages are not re-broadcast immediately. Only those queued messages which are ready to be sent (i.e. all those messages for which the timer has run out and which are still marked 'toSend') will be broadcast if they are coming from a vehicle driving towards the intersection. In the same thread, all messages which are older than their time-to-live are removed from the queue.

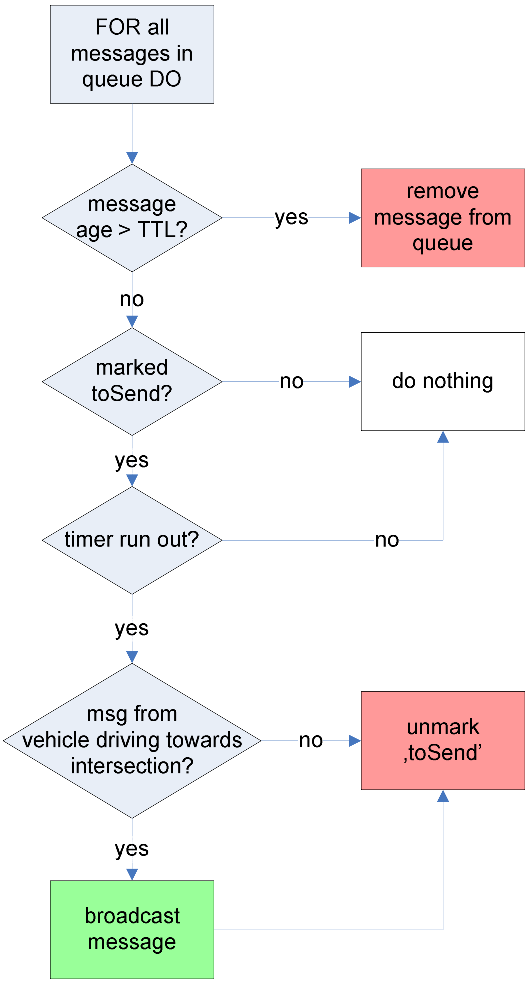

Figure 3.3: Queue routine run in thread

Outside the Area of the Intersection

The last path shown in Figure 3.1 represents the situation where a vehicle is not in the vicinity of an intersection. In this case no action is taken by the multi-hop algorithm.

3.4 Discussion

The proposed multi-hop routing protocol promises to solve the problem of reliable message dissemination in the intersection area by repeating and thereby relaying messages over selected vehicles. This should lead to a small communication overhead and should in most cases be adequate to reach all relevant vehicles as the radio range is sufficient to cover the whole intersection area [11]. No path discovery or maintenance is performed so that there are no interoperability problems with vehicles using legacy protocols. The only drawback is an added latency caused by the selection process of the relay vehicle. Because the expected increase in latency is small compared to the time-to-live of a message it should not impair the functionality of the assistance system. The proposed protocol should allow for low latencies even for heavy traffic since independent of the vehicle density only a small number of vehicles is re-broadcasting received messages.
The routing algorithm is only intended for the intersection assistance, which means that it will not create any load outside the intersection area and at the same time will not interfere with other multi-hop algorithms (e.g. for hazard warning dissemination).

Chapter 4

Implementation

This chapter shows the implementation details of the different components needed for the simulation environment. First the extensions to the ACUp communication framework and in a second part the Matlab/Simulink models are discussed.

4.1 ACUp Framework Extensions

The modular structure of the ACUp framework allows the use of different implementations of a layer or a component simply by launching the framework with a corresponding configuration file. A new implementation always inherits from the same base class like the already existing implementation and it has to follow the same basic structure for interfacing with the other components of the framework. All extensions described in this section are newly developed components which replace the existing ones.

4.1.1 Local Communication Interface

The ACUp framework is currently only used in the car where it is running on a DENSO wireless safety unit (WSU) [24]. For the simulation, a number of cars should be equipped with the framework and it is not sensible to connect as many hardware WSUs to the simulation system. To solve this problem, a new communication interface component has been implemented which allows for two ACUp frameworks to connect via TCP sockets instead of the IEEE 802.11p wireless interface used in the WSU.
The TCP connection is opened during startup of the framework and doesn't get closed until the framework is shut down. This way all packets can be sent and received without the necessity of opening a connection and going through the time consuming process of the three-way handshake. Additionally, the Nagle algorithm is disabled on the socket, which means that there is no wait time until a packet is full but data is always sent immediately. This increases the socket's responsiveness at the price of a possibly lower throughput due to the slightly decreased payload to header ratio. For the application at hand this is an adequate trade-off because latency is more important than throughput.

4.1.2 Framework Interconnection

To simulate a wireless LAN network, a client-server architecture has been implemented where the task of the the server framework is to reproduce the characteristics of the wireless communication (see Figure 4.1). To achieve that goal, it distributes received packets among the clients according to a predefined set of rules. The first condition is that clients are in communication range of each other. To determine whether this is the case, the server framework maintains a map of all connected clients along with their latest position. Once a new message is received, the distance from the sending client to all others is calculated. The message is forwarded to all clients which have a line of sight and are in communication range of the sender. Static obstacles (e.g. buildings) blocking the line of sight can be specified in the configuration of the server framework. If obstacles are defined, the server checks for each pair of clients which is in communication range whether there is an obstacle in their line of sight. It will only deliver the message if that is not the case. By applying these rules, the server framework reproduces the most important characteristics of the wireless communication. Further characteristics like diffraction, multi-path effects, packet collision or contention of the wireless medium are not reproduced in the simulation because they should not be required to evaluate the fundamental functionality of the multi-hop protocol.

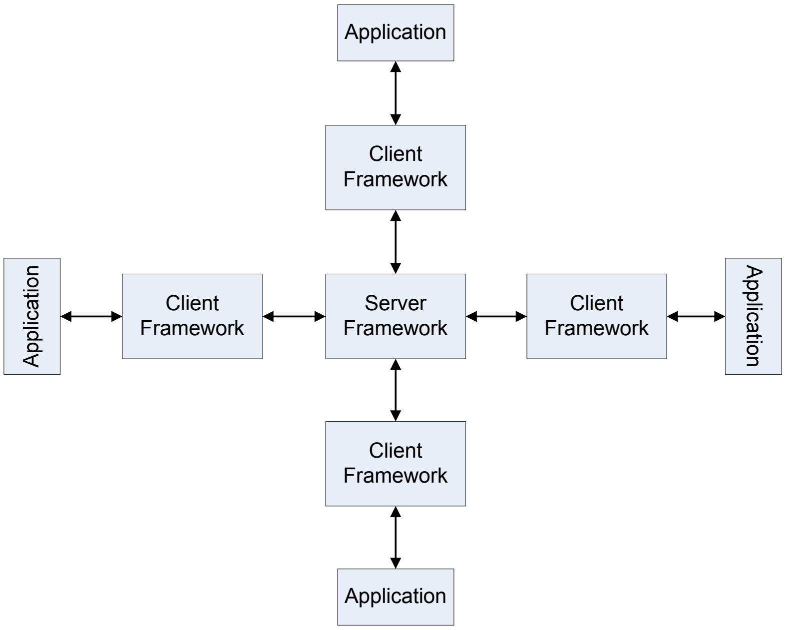

Figure 4.1: Framework interconnection

On startup, each client framework connects to the server via the communication interface described in Section 4.1.1. It then sends all messages received from the attached application (e.g. the intersection assistance system) to the server framework over the TCP connection. Because the time it takes to send a message over a local TCP socket is substantially shorter than to send it over the air, a random delay of 10 to 19 ms is added for each message by the client framework. This value is based on empirical values from transmissions with the 802.11p protocol on the WSU.

Due to the fact that every message in the simulation environment will pass the server framework, it is an ideal point to collect data for network traffic statistics. All incoming and/or outgoing messages can be logged and the data is stored in ASCII format in a comma-separated value file for later analysis.

4.1.3 Multi-Hop Routing Component

The multi-hop protocol described in Chapter 3 is implemented in a new ACUp routing component replacing the current one which is just a reference implementation without further functionality.

The first step towards realizing the protocol was to provide the necessary inputs to the ACUp framework. As already noted in Section 3.3, the algorithm requires the position information of the next intersection to calculate the time before a message is re-broadcast. Since this information is not yet included in the defined ACUp message format, the first step was to make this and all other required data available by adding the following fields to the message definition:

- coordinates of the next intersection
- size of the center of the next intersection
- time-to-live (as set by the application)
- hop count

The vehicle position information as well as the location of the next intersection are retrieved by the intersection assistant from the GPS navigation system with underlying digital road maps. By periodically checking the messages coming from the intersection assistance system, the current position of the own vehicle and of the upcoming intersection is now available to the routing component. Based on this information, one of the three paths depicted in Figure 3.1 is taken. The central area of the intersection is specified by the corresponding field in the message. A vehicle is defined to be inside the surrounding area when it is within a radius of 200m from the center of the intersection. This area should be sufficient even for situations where vehicles are approaching with high velocities. By defining a limited region, all messages concerning one intersection are contained in their relevant area.
A core component of the multi-hop protocol is the message storage which is realized with a C++ STL map. Received messages from neighbouring vehicles are added to the map and stored until their time-to-live runs out. The key value for the map is a pair of the source ID and the sequence number which uniquely identifies each message. The routines shown in Fig. 3.2 and Fig. 3.3 both operate on the same storage. Like this all currently queued messages will be sent out along with any newly received messages as soon as a vehicle reaches the center of the intersection.
To determine whether a received message is coming from a vehicle approaching the intersection before it is re-broadcast, the queue is searched for prior messages from the same source. If a previous message is found, the difference in distance to the center of the intersection is evaluated. If no previous message exists, more effort is required to determine whether a vehicle is driving towards the intersection. A predication can be made using the vehicle heading, the current position of the vehicle and the coordinates of the next intersection. This is currently not implemented because the message overhead caused by this exception is not crucial.
The last implementation detail to be discussed is the time that is set until a vehicle in the surrounding area of an intersection repeats a received message. The distance in meters from the receiving vehicle to the center of the intersection is doubled and the resulting value is set as the time to wait in milliseconds before the message is re-broadcast. This way, the closer a vehicle is to the center of the intersection, the shorter is the time until it will repeat the message. Since the distance a vehicle is traveling until the timer expires is very limited it is not necessary to take the driving direction or the speed of the vehicle into account.

4.2 Matlab/Simulink Models

To forward data coming from the traffic simulation in VISSIM to the ACUp framework, a new Matlab/Simulink model has been implemented. Its details are discussed in this section along with the adaptations of the KQA model implementing the intersection assistance system.

4.2.1 Send2ACUp Model

The Send2ACUp model essentially consists of two interconnected interfaces. The input to the model is coming from the VISSIM traffic simulation via the XFace interface discussed in Section 2.3. The complete list of variables which are read out from VISSIM is shown in Table 4.1.
For each simulation step this data is written to an ACUp message which is then forwarded to the framework via a C++ S-function using the client API of the framework.
To equip not only one but many vehicles in the simulation with the Send2ACUp functionality, the whole Simulink model is first compiled into C code with the Real-Time Workshop [25]. With that code, a shared library is created which can be attached to several vehicles in VISSIM. When the simulation starts, the vehicles connect to their respective ACUp framework and distribute their information to all other vehicles in range.

4.2.2 KQA Model

The existing KQA model had to be slightly adapted from its current use in the vehicle to the use in the simulation environment. The main difference is that in the car, all data is received over the CAN bus[1], whereas in the simulation the input is coming from VISSIM via the XFace interface.

[1] The Controller Area Network (CAN) is a vehicle bus standard designed to allow devices in the vehicle to communicate with each other

Variable Name	Data Type	Unit	Description
Acceleration	float	$\frac{m}{s^2}$	Current acceleration of the vehicle
AccelPedal	float	-	State of the accelerator pedal (0 = not pressed, 1 = fully pressed)
BackDriveLight	bool	-	State of the back-up light
BrakeLight	bool	-	State of the brake light
BrakePedal	float	-	State of the brake pedal (0 = not pressed, 1 = fully pressed)
HeadLight	bool	-	State of the headlight
HighBeamLight	bool	-	State of the high beam light
IndicatorLeftLight	bool	-	State of the left indicator light
IndicatorRightLight	bool	-	State of the right indicator light
MaxAcceleration	float	$\frac{m}{s^2}$	Currently available maximum acceleration
MaxDeceleration	float	$\frac{m}{s^2}$	Currently available maximum deceleration
OrientationYaw	float	rad	Vehicle heading with respect to north
Position	float	m	Vehicle position in x/y/z-coordinates
SlipAngle	float	rad	Side slip angle of the vehicle
SteeringWheelAngle	float	rad	Steering wheel angle
Vehicle ID	int	-	ID uniquely identifying a vehicle
Velocity	float	$\frac{m}{s}$	Current velocity of the vehicle
YawRate	float	$\frac{rad}{s}$	Yaw rate of the vehicle

Table 4.1: Send2ACUp variable list

For that reason the XFace input block used in the Send2ACUp model has been integrated in the KQA model.
Because several signals coming from VISSIM do not follow the specifications defined in the vehicle, a preprocessing block had to be implemented which adapts the inputs back to vehicle standards. In addition to some unit changes (e.g. radian to degree), the main difference is the way the heading of the vehicle is defined. Figure 4.2 shows the definition used in VISSIM and the GPS definition which is used in the vehicle. To adapt this input, a conversion block to change the heading from VISSIM to GPS norm has been implemented in Simulink. By applying this preprocessing, the same control system can be used in the Simulink model for both the simulation and the real-world applications. This also allows for an easy transfer of improvements from the simulation model to the model used in the vehicle and vice versa.

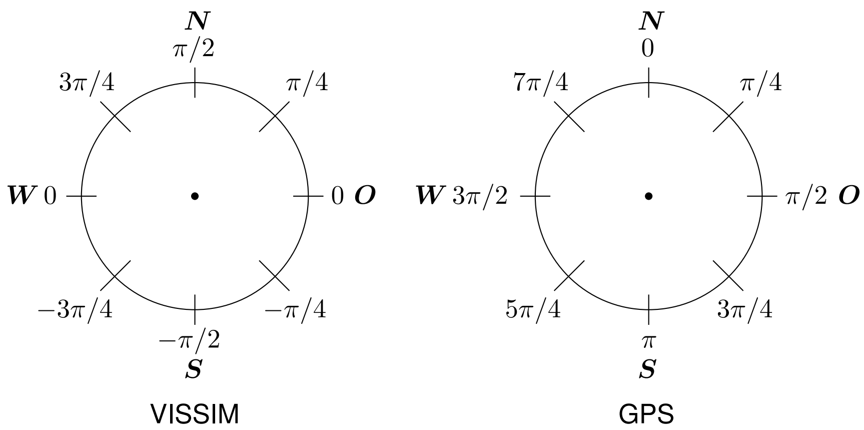

Figure 4.2: Definition for the vehicle heading in VISSIM and for GPS systems

To evaluate the suitability of the multi-hop protocol for the intersection assistance the Send2ACUp model is attached to all vehicles simulated in VISSIM. Only to one selected vehicle the KQA model is attached instead of the Send2ACUp model. The KQA model is run directly in Simulink as a co-simulation to VISSIM which allows for a recording of interesting data (e.g. the time a warning is issued to the driver) in the Matlab workspace to evaluate the performance of the intersection assistance in different scenarios. To attach the KQA model to every vehicle would require much higher computing power and is not necessary to evaluate the developed multi-hop protocol.

4.3 Discussion

Starting point for the implementation of the simulation environment discussed in this chapter was the real-world system shown in Figure 4.3. The data exchange between the vehicle and the KQA system is done over the CAN bus. To get communication messages to the ACUp framework, they are sent again on the CAN bus to an application which converts them to the ACUp format and sends them via the client API to the framework running on the WSU. From there they are broadcast to all vehicles in transmission range with the IEEE 802.11p draft standard.

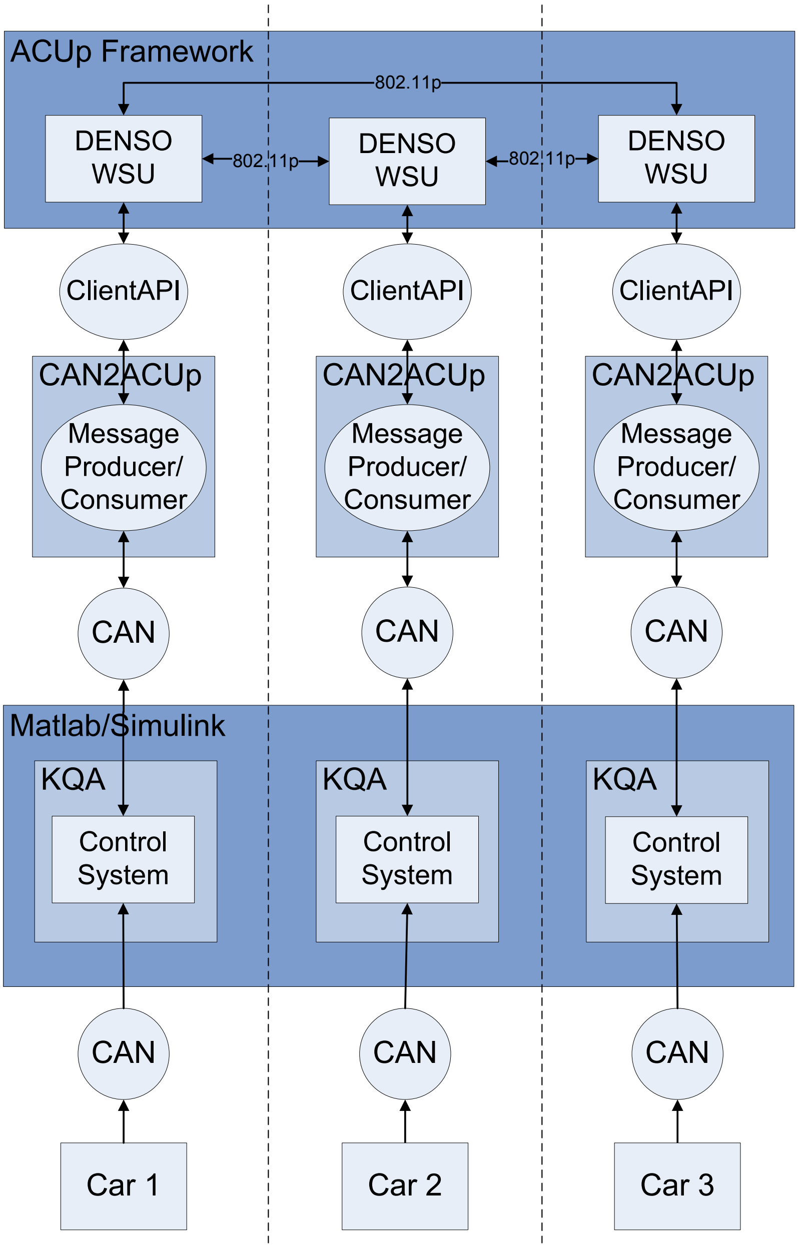

Figure 4.3: Intersection assistance system in the car

The goal of the newly devised simulation environment is to use as many components of the existing system as possible so that any development done in the simulation can easily be trans-

ferred to the real system used in the vehicle. Figure 4.4 shows the whole simulation environment. The core components (i.e. the KQA control system and the ACUp framework) are the same for the simulation and the real-world application. The main difference is the way data is passed along the various components.
Because no CAN bus exists for the cars simulated in VISSIM, the XFace interface is used instead. The communication with the ACUp framework is realized by accessing the client API directly from Matlab instead of using the intermediate CAN2ACUp application and for the interconnection of the frameworks, TCP connections are used rather than the wireless LAN interface. This structure allows for a flexible setup where the components are either all run on one machine or where they are distributed among different computers. It is possible to run VISSIM, the co-simulation of the KQA model, the client frameworks and the server framework all on different machines to efficiently distribute the generated CPU load for comprehensive simulations.

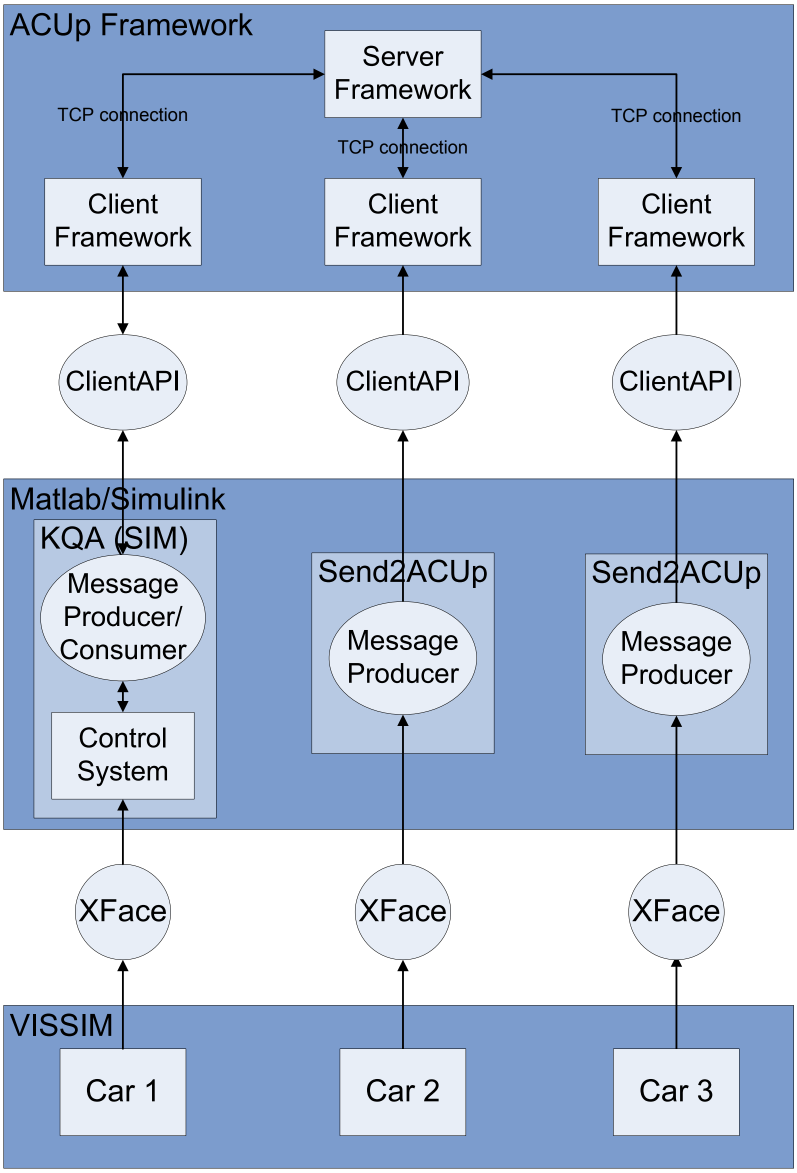

Figure 4.4: Intersection assistance system in the simulation

Chapter 5

Functional Evaluation and First Real-World Experiments

In this chapter the results of the evaluation of the enhanced intersection assistance system are presented. First the findings from the simulation are reviewed followed by the analysis of the real-world test and by a final discussion of the improvements achieved with the multi-hop approach.

5.1 VISSIM Simulation

5.1.1 Intersection Scenarios

For the simulation in VISSIM, the intersection scenario depicted in Figure 5.1 has been created. It consists of two perpendicularly crossing streets with one lane in each direction (numbered 1-4). Both streets are 630m long and each lane is 3.5m wide. There is no special traffic regulation and the priority to right rule applies. To simulate the line of sight obstruction, one up to four obstacles are placed at the corners of the intersection (numbered *1-4*). These square obstacles each have a surface area of 72mx72m and represent buildings. The layout of the intersection has been selected to simulate the case where a single-hop communication cannot be established until the approaching car reaches the center of the intersection due to line of sight obstructions.

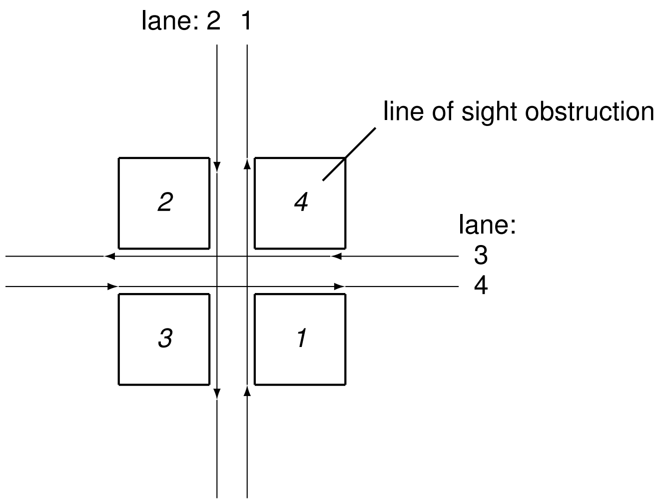

Figure 5.1: VISSIM intersection scenario

The chosen scenario represents a situation often encountered in an urban area where the streets are mostly bordered by buildings constraining the sight into a crossing road and prohibiting direct communication. In the following section the performance in terms of message dissemination of the intersection assistance system is evaluated for scenarios with different obstruction combinations with and without the multi-hop enhancement.

5.1.2 KQA Performance

The performance of the intersection assistance system is defined by the timely warning of the driver about an upcoming yielding disregard. To study the behaviour of the system, the following scenario is set up in the simulation: One car is put at the beginning of each lane driving with a speed of about 60$\frac{km}{h}$towards the intersection. The cars driving on lane 2 and 4 follow the traffic regulation and give way to the other vehicles whereas cars 1 and 3 disregard the regulation and are not decelerating when approaching the intersection. The assistance system is running in the car on lane 1 and it should always issue a warning about a yielding disregard for the right of way vehicle driving on lane 3.
The distance at which a warning is displayed is calculated with equation (5.1). It computes the total stopping distance which is composed of the distance travelled during the reaction time of the driver and the actual braking distance.

$$x_{stop} = \underbrace{\frac{v_0^2}{2 \cdot a}}_{\text{braking distance}} + \underbrace{t_{reac} \cdot v_0}_{\text{reaction distance}} \tag{5.1}$$

With the values defined for the simulation ($t_{reac} = 1s$, $v_0 = 16.33\frac{m}{s}$, $a = 6\frac{m}{s^2}$) a stopping distance of 38.55m is resulting at which the system should be issuing a warning to the driver.
Table 5.1 shows the actual warning distance in the simulation for different obstacle configurations. The difference between the calculated and the actual distance is caused by measurement uncertainty for the map in VISSIM. The radio range is set to 100m for all vehicles. This value is based on experiences made so far with the IEEE 802.11p hardware on the DENSO WSU. Since the hardware is running with a very low transmission power and generally is still in a very early stage, the final standard is likely to show a better performance.

Obstacle(s)	-	*1*	*1,2*	*1,2,3*	*1,2,3,4*
Single-Hop	38.42m	7.39m	7.39m	7.39m	7.39m
Multi-Hop	38.42m	38.42m	38.42m	38.42m	7.39m

Table 5.1: Distance at which a warning is issued (radio range = 100m)

For the open field case with no line of sight obstructions, both the single-hop and the multi-hop routing protocol show the same performance. If obstacle *1* is added to the scenario however, the assistance system is not able to issue a warning on time using the single-hop communication. During the approaching phase, no direct line of sight is available anymore between vehicles 1 and 3 which means that those two vehicles don't receive any information about each other. Therefore the warning only appears way too late when both cars are almost in the center of the intersection and a collision cannot be prevented anymore. With the devised multi-hop protocol however, the messages from vehicle 3 are reliably relayed to vehicle 1 via vehicle 2 or 4 and therefore the warning is displayed in time. This is also the case when obstacles *2* and *3* are added. A successful message exchange is possible using the multi-hop protocol and the system still works fine. Only in the last scenario with all four obstructions in place, a timely warning is inhibited because there is no car which is able to relay the messages from vehicle 3 to vehicle 1.
To determine the influence of the radio range, some of the scenarios have been simulated with a doubled range of 200m. The results shown in Table 5.2 indicate that a larger range does not improve the performance of the intersection assistance system in this scenario. Neither the performance of the single-hop approach with only one obstacle nor the multi-hop routing with all four obstacles is improved due to the better radio range.
Enabling a successful message exchange for the scenario with four line of sight obstructions would require a relaying vehicle in the center of the intersection. Having such a vehicle is infrequent for low to medium vehicle densities. Only with a very high vehicle density the performance of the multi-hop protocol would presumably increase for the case of four line of sight obstructions. A solution to this problem would be to install a permanent roadside unit (RSU) on the intersection to act as a communication partner for approximating vehicles. This is an especially

Obstacle(s)	-	*1*	*1,2,3,4*
Single-Hop	38.42m	7.39m	7.39m
Multi-Hop	38.42m	38.42m	7.39m

Table 5.2: Distance at which a warning is issued (radio range = 200m)

promising approach if the communication units, which will be installed for the traffic light assistance [26], could also be used for the message dissemination of the intersection assistance. In the simulation, an RSU running the same multi-hop protocol used in the vehicles has been placed in the central area of the intersection to study the resulting benefits. Table 5.3 lists the outcome of the simulation which shows that a timely warning can be issued with an RSU in place even when all four corners of the intersection are occupied by buildings.

Obstacle(s)	-	*1*	*1,2*	*1,2,3*	*1,2,3,4*
Multi-Hop	38.42m	38.42m	38.42m	38.42m	38.42m

Table 5.3: Distance at which a warning is issued (radio range = 100m), RSU on the intersection

5.1.3 Single-Hop vs. Multi-Hop Routing Performance

In addition to the functional evaluation of the KQA system it is also essential to analyse the general network properties of the new multi-hop routing protocol and compare them with the presently used single-hop communication. Three important characteristics are studied in the following subsections: the message dissemination, the channel utilization and the message latency.

Message Dissemination

The main goal of the multi-hop approach is to enable a successful message exchange between all vehicles which are relevant to each other concerning the intersection assistance system. The evaluation of this performance feature can either be done on the application level as presented in Section 5.1.2 or on the network level. Since the relevance between the vehicles is changing constantly as they approach an intersection, it is quite difficult to evaluate the performance from a network point of view where the required relevance information is not available. However, to get an idea of how efficient the message dissemination is, the average number of vehicles reached per message is examined. This serves as an indicator on how well messages are distributed among the vehicles. The evaluation has been done on the same scenarios as discussed in Section 5.1.2 and the results for the different routing protocols are shown in Figure 5.2.
The number of vehicles reached by any message can vary between 0 and 3 since there is a total of 4 vehicles in the studied scenarios. Because at the beginning of the simulation the vehicles are not in communication range of each other, messages that are sent at this point are not received by any vehicle. These messages are not considered for the presented average value. During the approaching phase the vehicles get in communication range of each other and the RSU.
The statistics serve to show the *difference* in connectivity for the different protocols. The goal is not to study the absolute values.
As can be seen from the graph, the multi-hop routing always achieves a better message dissemination than the single-hop routing. In the scenarios with 2 and 3 obstacles, the average number of vehicles reached by each message is more than 20% higher which demonstrates the effectiveness of the multi-hop approach. Only in the scenario with obstructions at all four corners of the intersection there is a noticeable drop which correlates with the findings in Section 5.1.2.
If a roadside unit is available, the message dissemination stays at an almost constant level for 2 to 4 obstacles. This confirms its benefit for intersections which are heavily blocked with line of sight obstructions as it allows for a successful message exchange even in these scenarios.
The somewhat unexpected rise in the number of vehicles reached in the scenario with one obstacle is due to the absence of a direct communication between vehicles 1 and 3 approaching

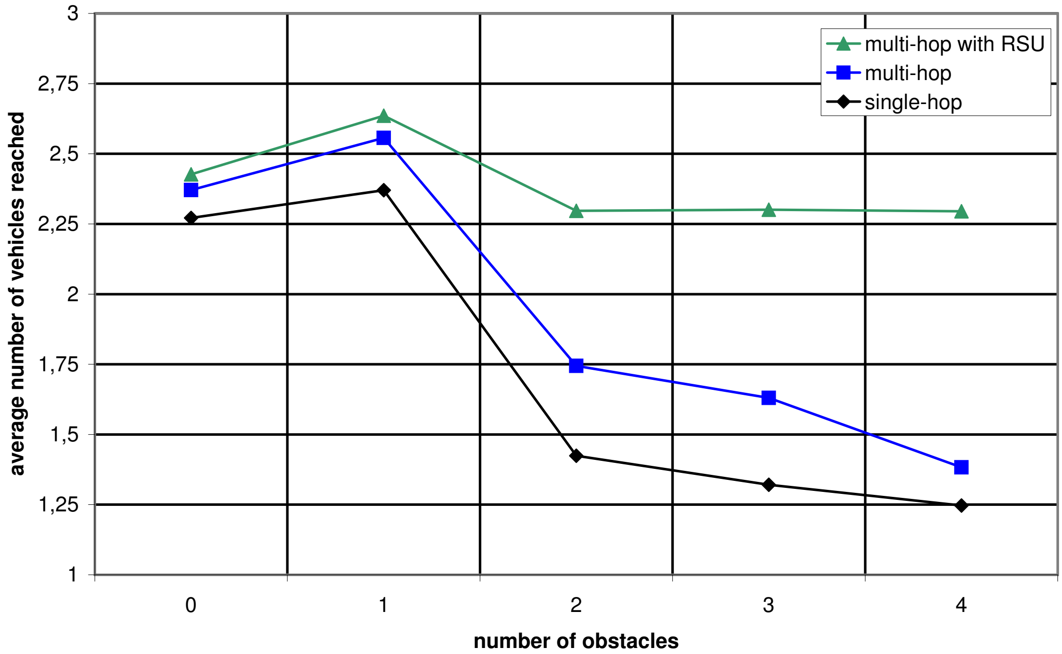

Figure 5.2: Average number of vehicles reached by each message

the intersection. This leads to a smaller number of messages which reach just one other vehicle and in return to a higher average number of vehicles reached.

Message Latency

Since the intersection assistance system depends on up to date information about all surrounding vehicles, an important parameter is the time it takes from when a message is sent, to the moment when it arrives at its destination. For that reason the change in latency has been studied for the newly devised multi-hop protocol.
The same scenario with 4 vehicles approaching the intersection and different obstacle configurations has been evaluated. Figure 5.3 shows the average value of the latency for all received messages for the different routing protocols.

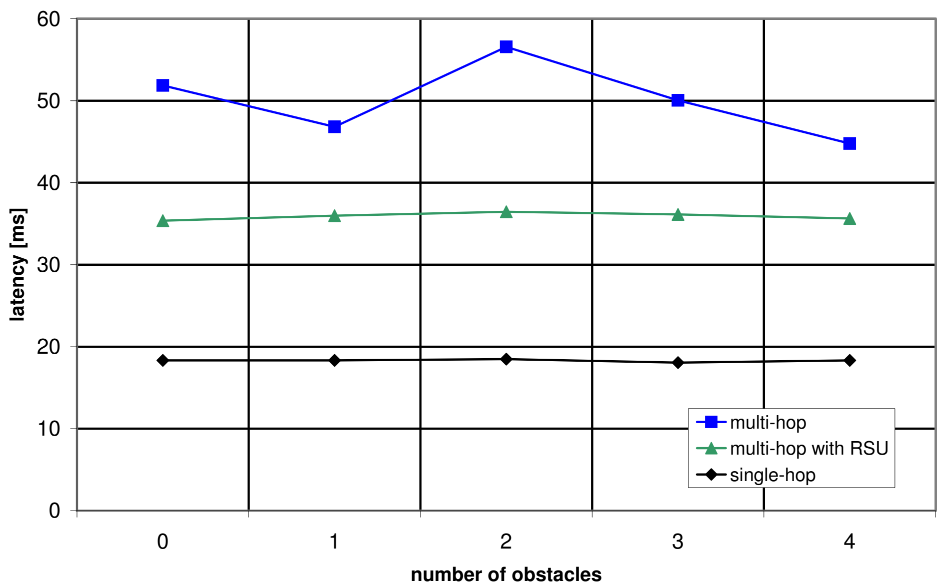

Figure 5.3: Average message latency

Since the current wireless LAN emulation does not implement media access contention or message collisions, the one hop latency is just defined by a random offset of 10 to 19ms to the time it takes to send a message over the TCP connection. This results in an almost constant average value for the single-hop latency for all obstacle configurations. The statistics for the multi-hop routing protocol in contrast shows a considerable dependence on the simulated scenario. The reason for this is the timer which gets set in each vehicle according to its distance from the center of the intersection. Depending on the particular situation, no car might be close to the center which in turn leads to an additional latency because the message isn't re-broadcast until the timer has expired. The maximum average value for the latency is 57ms in the scenario with 2 obstacles. The time-to-live of a message is set to 500ms by the intersection assistance system so that an average value of 57ms is still well within the range of tolerance.
If a roadside unit is installed on the intersection, the latency is almost constant for the different scenarios because the RSU will repeat all incoming messages in the intersection area without delay. This mostly eliminates the variation observed without an RSU. The fix increase in latency compared to the single-hop routing is due to the addition of a second one hop latency for all multi-hop messages.

Channel Utilization

The last statistics studied on the network level is the utilization of the communication channel. To determine the wireless network load, the number of messages that are sent by all vehicles during one simulation run is analysed. Figure 5.4 shows the total number of sent messages for both the single-hop and the multi-hop routing protocol for a different number of vehicles approaching the same cross intersection used in the previous evaluation tasks.

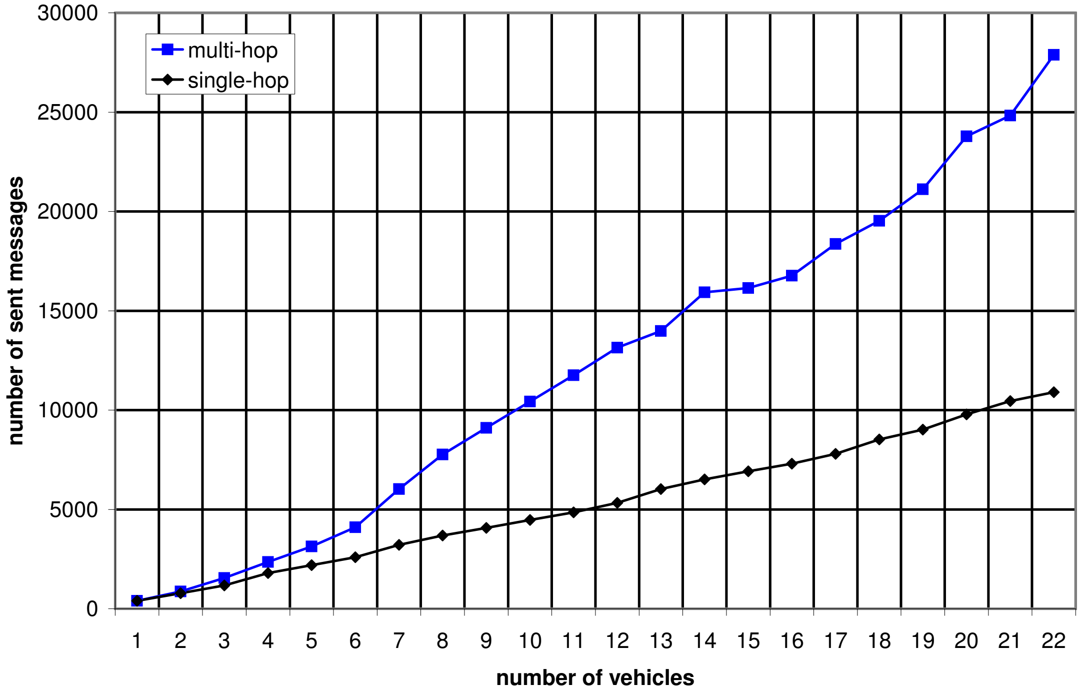

Figure 5.4: Total number of sent messages, no obstacles

The number of ACUp communication frameworks that can be run simultaneously on one computer together with the simulation in VISSIM is limited because of the consumed computing power. The machine used for the simulation is a Pentium IV with 3.4GHz and 2GB of RAM with which up to five vehicles can be simulated. To evaluate scenarios with more vehicles concurrently approaching the intersection, the possibility to distribute the load to more than one machine has been used as discussed in Section 4.3. For the evaluation of the channel utilization VISSIM and the server framework are running on one system and all the client frameworks are executed on a second machine connected via a local area network.

The simulated vehicles are evenly distributed among the different branches and there are no obstacles placed around the intersection. At some point during the simulation, this leads to a challenging situation for the multi-hop protocol where all 22 vehicles are in the intersection area and in communication range of each other.
Using the single-hop routing protocol, the number of sent messages increases linearly with the number of vehicles used for the simulation as each new vehicle sends a fixed amount of additional messages. As can be observed in Figure 5.4, the multi-hop protocol displays an approximately linear increase in the number of sent messages as well. This demonstrates the efficiency of the devised algorithm in achieving a good message dissemination without creating a disproportionate overhead. For up to a number of 7 vehicles not even twice the amount of messages is generated and even with 22 vehicles in the intersection area, the number of sent messages does not exceed three times the amount used with the single-hop protocol.
To further study the characteristics of the multi-hop protocol, the same scenario has been evaluated with the addition of line of sight obstructions. Figure 5.5 shows the collected statistics using the multi-hop protocol for one up to four obstacles added around the intersection.

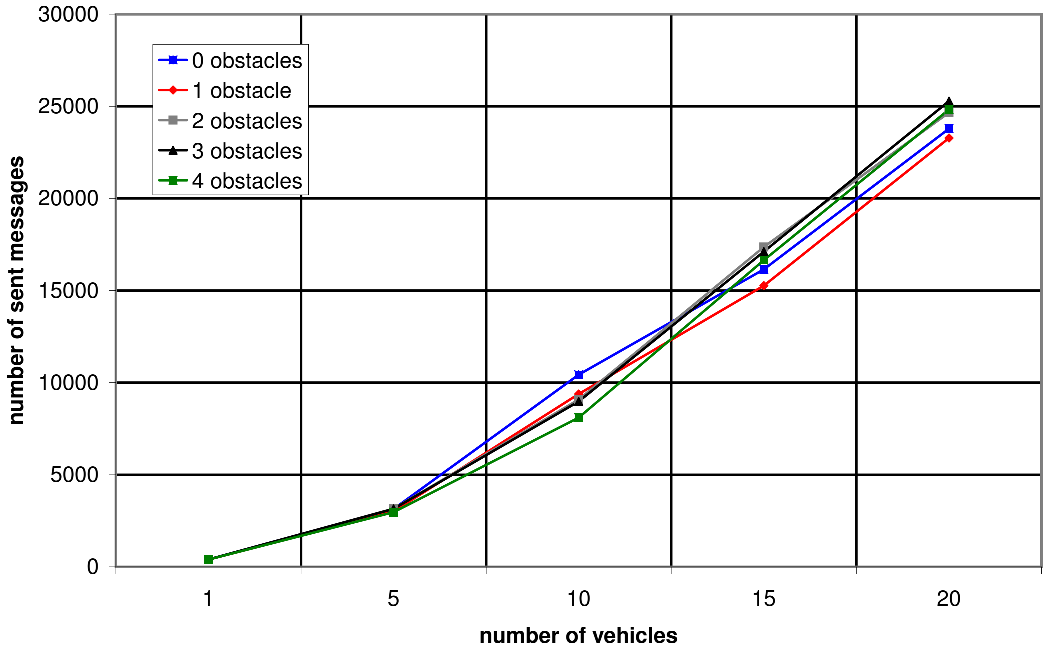

Figure 5.5: Total number of sent messages, multi-hop routing protocol

It can be observed that the difference in messages sent for the same amount of vehicles with different line of sight obstructions varies up to 15% but there isn't a single scenario which causes a clear increase in sent messages for any number of cars.

5.2 Real-World Test

After evaluating and optimizing the multi-hop protocol in the simulation environment, the goal was to get the developed ACUp routing component running on the system used in the car (cf. Fig. 4.3) and evaluate its functionality in a real-world test. To achieve this goal several smaller adaptations needed to be incorporated. Two new CAN messages had to be defined to allow the exchange of the information about the next intersection and due to those extensions the CAN2ACUp application had to be adapted as well.
In addition, all the position informations are exchanged in WGS 84 coordinates [27] between the vehicles and not in a metrical coordinate system like in the simulation with VISSIM. To apply the same algorithms used for the simulation, the WGS 84 coordinates are transformed into Gauß-Krüger coordinates [28] which offer a metrical, Cartesian coordinate system and are often used for cartography purposes in Germany. By first applying this transformation it is possible to use the same routing component for both the simulation and the real-world application.

5.2.1 Intersection Scenario

The intersection at which the assistance system has been tested is located in the north-west part of Munich near the BMW Group Research and Technology office. Two streets called 'Gneisenaustraße' and 'Messerschmidtstraße' are crossing at a T-intersection. The intersection is interesting for the evaluation of the multi-hop protocol because there are line of sight obstructions in the form of office buildings at both corners of the intersection. These obstacles prohibit a single-hop communication between vehicles approaching from different directions.
In the evaluated scenario one car is driving south on the Messerschmidtstraße while the other is driving east on the Gneisenaustraße as shown in Figure 5.6. The priority to right rule applies at the intersection so that the car driving south has to give way to the other vehicle.

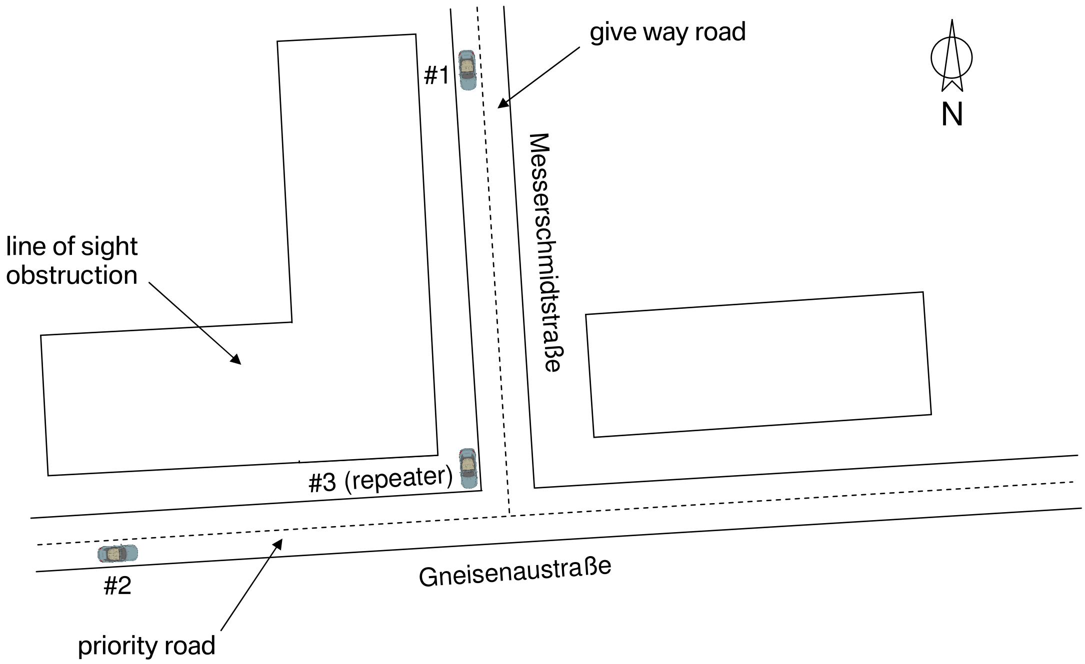

Figure 5.6: Intersection used for the real-world evaluation

5.2.2 KQA Performance

To enable a multi-hop communication in the given scenario, a third car is placed right at the corner of the intersection. Car #3 is not driving because the coordination of three vehicles at a public intersection with traffic would have been too difficult for the conducted test.
All three vehicles are equipped with the DENSO WSU executing the ACUp communication framework with the developed multi-hop routing protocol and on vehicles #1 and #2 the intersection assistance system is running.
Cars #1 and #2 are approaching the intersection at the same time so that the driver of car #1 should receive a warning about a potential yielding disregard. Table 5.4 shows the distance between vehicle #1 and the center of the intersection at which vehicle #1 first receives a message from vehicle #2 using multi-hop communication for two test runs. The difference between the two test runs stems from the real test setup which varies slightly with each attempt.

Test run #	Distance (m)
1	60.94
2	66.34

Table 5.4: Distance from vehicle #1 to the center (multi-hop communication)

With a speed limit of 50$\frac{km}{h}$ these transmission distances are sufficient for the intersection assistance system to warn the driver about the imminent yielding disregard. According to equation (5.1) the theoretical maximum speed at which a successful functioning of the assistance system is still ensured is 78$\frac{km}{h}$ for a distance of 60.94m. Since the vehicle is approaching the intersection with about 32$\frac{km}{h}$ the driver is correctly warned about the yielding disregard for both test runs.
To evaluate the same situation using single-hop communication for comparison, the WSU in vehicle #3 is disabled. The result for this scenario is listed in Table 5.5.

Run #	Distance (m)
3	30.66
4	20.23

Table 5.5: Distance from vehicle #1 to the center (single-hop communication)

For the worst case in test run 4, the warning distance equates to a maximum velocity of 38.5$\frac{km}{h}$. No assistance can be provided to the driver for higher speeds using single-hop communication. These findings confirm the benefit of the multi-hop protocol for intersections with line of sight obstructions and they verify the functionality of the developed routing protocol in the real world.

5.3 Discussion

The evaluation of the proposed multi-hop algorithm showed promising results both in the simulation and during initial tests with real cars. The goals formulated in Chapter 3 are mostly attained.
In the simulation environment, the objective of a more reliable communication on intersections with no line of sight between adjacent branches by using the devised multi-hop algorithm was achieved with a manageable increase in latency and little extra load on the network. To further improve the probability of a successful message exchange on intersections with manifold obstructions the application of a roadside unit was identified to be a promising solution, especially if already existing installations could be used for this purpose.
In a second step, the results from the simulation environment could also be verified in a small field test with three communication partners where a reliable operation of the intersection assistance system could only be achieved by using the developed multi-hop protocol.

Chapter 6

Conclusion

The subject of this thesis is the performance enhancement of an intersection assistance system based on wireless ad-hoc car-to-car communication. Vehicles in the intersection area exchange information about their current status (e.g. speed, position, heading). Based on this information a warning is issued to the driver if he is about to disregard the right of way of an approaching vehicle. First evaluations have shown that the risk of vehicle collisions at intersections can be significantly reduced by the application of the intersection assistance system.

In the existing system using the ACUp framework [12], any information exchange is limited to single-hop communication which requires the availability of a direct wireless LAN connection between every the pair of vehicles that should benefit from the intersection assistance system. This single-hop communication proved to be insufficient since the communication range of the employed IEEE 802.11p draft standard is very limited and since there is often no direct line of sight between vehicles approaching an intersection, especially in urban areas.

This master thesis therefore aimed at improving the performance of the assistance system by extending the ACUp framework from single-hop to designing and implementing multi-hop communication. By allowing other vehicles and infrastructure to repeat and thereby relay a received message, the propagation of information was expected to be greatly improved.

To evaluate the effectiveness of the enhanced system, a simulation environment was set up which included all core elements of the real-world system. This had the advantage that the entire intersection assistance system and not only the communication could be assessed in the simulation. The simulation environment was based on the traffic simulation VISSIM, extended by the possibility to simulate the vehicular ad-hoc network. This offered an advantageous way to model various settings with different traffic characteristics given the fact that in the real world currently only a very limited number of specially equipped research vehicles are available.

The evaluation in the simulation environment has shown that the routing module enhanced with multi-hop functionality allows for a much more reliable operation of the assistance system compared to the previous single-hop communication. The problem of a missing line of sight between two vehicles could be mitigated to a large extent by using other vehicles as message relays. In the simulation, the single-hop communication allowed for a warning distance of only 7.39m with 3 line of sight obstacles, which effectively is not sufficient. Using the multi-hop protocol a successful warning at a distance of 38.42m was possible.

Only for intersections which were heavily blocked with line of sight obstructions, a reliable message dissemination couldn't be adequately provided. For this scenario, the application of roadside units acting as relays proved to be a valuable extension to greatly increase the chances of a successful communication between approaching vehicles. With a roadside unit in place a warning distance of 38.42m could be achieved even with 4 line of sight obstructions, one in every corner of the intersection. This extension proved to be a viable solution of the problem since the installation of communication units at intersections is already planned in connection with other projects (e.g. traffic light assistance). This increases the benefits of the developed multi-hop protocol as it is applicable for both the vehicle and the infrastructure units.

Together with the improved results for the intersection assistance, the implications of the multi-hop routing on the ad-hoc network has been analysed. The findings from the simulation indicate that neither the latency nor the wireless channel utilization exhibit a problematic increase due to the application of the new routing algorithm. The number of additional messages that are sent when the multi-hop protocol is used, increases only linearly and the latency is still well below a critical level for the actuality of the messages. These results further support the suitability of the developed multi-hop protocol to effectively enhance the performance of the intersection assistance system.

As a last step, the developed extended system was ported back to research vehicles and tested on the road with three communication partners. In the chosen test environment no reliable assistance was possible using single-hop communication because a building obstructing the line of sight reduced the maximum speed for a successful warning of the driver to $38.5\frac{km}{h}$. By running the same test with the devised multi-hop protocol in place, the driver was warned about the potential disregard of the right of way in time up to a speed of $78\frac{km}{h}$. This has proved the effectiveness of the developed routing protocol in the vehicle and it is to the best of the author's knowledge the first time a multi-hop algorithm for the application on an intersection has been successfully tested and documented in a real-world application.

Chapter 7

Outlook

It would be very interesting to further assess the enhanced intersection assistance system in a more comprehensive real-world test involving more than three communication partners. The evaluation of the multi-hop protocol showed quite promising results in a small field test which should be verified in subsequent test scenarios. This is planned as part of the SIM-TD project [8] where several hundred vehicles will be equipped with communication units. Different driving assistance systems will be evaluated to determine the benefit of Car2X communication for traffic safety and the developed intersection assistant will be one of those applications. It will be very exciting to see how well the multi-hop communication is going to perform under these circumstances and where possible improvement could be achieved.

Future work could also pursue optimizations for the simulation environment. To get more realistic wireless LAN characteristics, a more sophisticated simulation model could be implemented. To achieve this goal, one could try to establish an interconnection of the server framework with a network simulator (e.g. the well known ns-2 [29]). This way already existing simulation implementations of the IEEE 802.11p draft standard (e.g. the one presented in [30]) could be utilized for the developed simulation environment.

To get an even more realistic simulation of the intersection assistance system, its output could be used as an input to the car in VISSIM so that it would react the same way a car in reality would.

To further improve the performance of the KQA, the current density of vehicles could be considered as proposed in [18] to determine the rate at which new messages are emitted. This could help ease the load and possible congestion of the wireless channel without reducing the reliability of the driver assistance. Another idea, which is already planned for the ACUp framework but has not yet been implemented, is the possibility to aggregate several messages in one packet. This would improve the contention problem since a node would not need wireless media access for every message. Especially for a vehicle in the center of the intersection or a roadside unit this could be a big advantage since these nodes often have to send a lot of messages in a very short timeframe. The downside of this approach would be an added latency because messages are aggregated before they are sent out. A good trade-off would have to be found between media access contention and additional latency.

A completely different approach to solving the problem of car-to-car communication is studied in the AKTIV Project Cooperative Cars (CoCar) [31]. The idea here is not to use mobile ad-hoc networks to exchange information but to rely on cellular mobile communication technologies (UMTS, HSPA, LTE) which are currently used for mobile telephone and data applications. The main problem using cellular communication is the high latency which until now prohibits the use in time-critical driver assistance systems (e.g. intersection assistance). As the technology evolves, the performance increases constantly, so that even time-critical systems might operate with sufficient performance using these means of communication in the near future. If the CoCar project proves that next generation cellular communication is suitable for time-critical car-to-car applications, an integration of that system into the intersection assistant would be conceivable and could offer another gain in reliability of the message exchange.

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Appendix A

Schedule and Work Progress

Week	Date	Primary Task	Deliverables
1	15.09.-19.09.	Familiarization with VISSIM	
2	22.09.-26.09.	Familiarization with ACUp Framework	
3	29.09.-03.10.	Familiarization with ACUp Framework	
4	06.10.-10.10.	Familiarization with ACUp Framework	Schedule
5	13.10.-17.10.	Begin implementation of local communication interface	
6	20.10.-24.10.	Finish implementation of local communication interface	
7	27.10.-31.10.	Begin implementation of framework interconnection	
8	03.11.-07.11.	Finish first implementation of framework interconnection	
9	10.11.-14.11.	Begin implementation of Send2ACUp model	
10	17.11.-21.11.	Finish implementation of Send2ACUp model	
11	24.11.-28.11.	Preparation of informal presentation, literature research (current state of the art)	Informal presentation (Dr. Spyropoulos)
12	01.12.-05.12.	Draft of the multi-hop protocol	
13	08.12.-12.12.	Adaptations of the KQA model for the simulation	
14	15.12.-19.12.	Begin implementation of the multi-hop protocol	
15	22.12.-26.12.	Implementation of the multi-hop protocol	
16	29.12.-02.01.	Implementation of the multi-hop protocol	
17	05.01.-09.01.	Finish first implementation of the multi-hop protocol	
18	12.01.-16.01.	Extension of framework interconnection	
19	19.01.-23.01.	Preparation of intermediate presentation, optimization of multi-hop protocol	
20	26.01.-30.01.	Adaptation of current message format for multi-hop protocol to run on WSU	Intermediate Presentation (Prof. Plattner)
21	02.02.-06.02.	Performance evaluation in simulation	
22	09.02.-13.02.	Performance evaluation in simulation	
23	16.02.-20.02.	Composition of report	
24	23.02.-27.02.	Composition of report, performance evaluation in simulation	
25	02.03.-06.03.	Composition of report, performance evaluation in the car	
26	09.03.-13.03.	Completion of report and final presentation	Report

Table A.1: Schedule

Appendix B

Task Description

Master Thesis

Performance Enhancement of an Intersection Assistance System by Integrating WLAN Ad-Hoc Network with Multi-Hop Capabilities

In order to reduce the number of traffic accidents despite of today's increasing traffic volume, driver assistance systems have been developed. Within the German nationally-funded research project AKTIV (**A**daptive und **k**ooperative **T**echnologien für den **I**ntelligenten **V**erkehr – Adaptive and Cooperative Technologies for Intelligent Traffic) BMW is developing a driver assistance system which identifies potentially critical traffic situations at intersections between a give way vehicle and a priority vehicle using vehicle to vehicle communication (WLAN ad-hoc network): If the driver does not recognize a critical situation, a warning will be emitted.
If some obstruction exists within the line of sight between two vehicles, frequently no direct data exchange will be possible and system performance will be affected. To overcome this, messages can be transmitted via other communication partners, e.g. other vehicles.

In order to implement relaying, within this master thesis a WLAN ad hoc network with multi-hop ability will be integrated into the intersection assistance system. Thereby an exchange of data will be possible between two vehicles approaching an intersection, even when their intervisibility is impaired. In detail, the following subtasks have to be addressed:

- integration of a framework for vehicle to vehicle communication (source code is available) into a traffic simulation program
- integration of an intersection assistance system (a Simulink model is available) into this traffic simulation program
- integration of multi-hop data transmission by means of an ad-hoc network instead of the currently used single-hop broadcasting
- selection and design of test scenarios reflecting the road network of a subsequently planned field operational test
- porting of the system which has been developed within the traffic simulation program to a test vehicle
- functional evaluation of the system developed using either simulation or a real test scenario
- documentation and presentation of results

The master thesis should document the tasks and procedure in a clearly structured manner. Furthermore the candidate is committed to compose his master thesis independently and to quote scientific resources used.

Tutor:

Dr. Peter Zahn, e-mail: peter.zahn@bmw.de, Tel.: +49-(0)89-382-45003

Dr. Felix Klanner, e-mail: felix.klanner@bmw.de, Tel.: +49-(0)89-382-14601

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BMW Research and Technology GmbH

BMW Group
Research and Technology

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