Situation-Aware Vehicles
Situation-Aware Vehicles
Supporting the Next Generation of Cooperative Traffic Systems
Abstract

Wireless communication between road vehicles enables a range of cooperative traffic applications including safety, efficiency and comfort functions. A common characteristic of the envisioned applications is that they act on environmental information to interpret traffic situations in order to provide the driver with warnings or recommendations. In this thesis we explore both the detection of hazardous traffic situations in order to provide driver warnings but also the detection of situations in which the cooperative system itself may fail.

The first theme of this thesis investigates how traffic safety functions that incorporate cooperatively exchanged information can be constructed so that they become resilient to failures in wireless communication. Inspired by how human drivers coordinate with limited information exchange, the use of pre-defined models of normative driver behavior is investigated by successfully predicting driver turning intent at an intersection using mobility traces extracted from video recordings. Furthermore a hazardous driving warning criterion based on model switching behavior is proposed and evaluated through test drives. Maneuvers classified as hazardous in the tests, such as swerving between lanes and not braking for traffic lights, are shown to be correctly detected using the criterion. Whereas robust coordination mechanisms may mask communication faults to some degree, severe degradations in communication are still expected to occur in non-line-of-sight conditions when using wireless communication at 5.9 GHz.

The second theme of the thesis explores how communication performance can be efficiently logged, gathered and aggregated into maps of communication quality. Both in-network aggregation as well as centralized aggregation is investigated using vehicles in the network as measurement probes and the feasibility of the approach in terms of bandwidth and storage requirements is shown analytically. In conjunction with a proposed communication quality requirements format, tailored specifically for vehicle-to-vehicle applications, such maps can be used to enable application-level adaptation in response to situations where quality requirements likely cannot be met.
Acknowledgements

First of all I would like to thank my main supervisor Tony Larsson for the support and guidance in carrying out the research presented in this thesis and for leading me on the path towards becoming an independent researcher. Thanks also go to my co-supervisor, Mattias Broxvall of Örebro University, for his assistance and advice during the thesis work.

Without the assistance from all the colleagues at Halmstad University much of this work would not have been possible. My friends and co-workers at CERES all have my gratitude, special thanks to Elisabeth Uhlemann, Magnus Jonsson and Bertil Svensson. For helping get me to the right places, helping buy lab equipment and catering to sometimes very specific demands on test car rentals I would like to acknowledge the support of the administrative staff; Eva Nestius, Jessika Rosenberg and Christer Svensson. To Magnus Larsson I am grateful for the confidence in letting me enter Halmstad University in the Grand Cooperative Driving Challenge and to Emil Nilsson for the support through e-lab.

To my fellow Ph.D. students, Annette Böhm, Katrin Sjöberg, Dr. Zain-ul-Abdin, Dr. Yan Wang and Dr. Edison Pignaton de Freitas; it has been a true pleasure working with you all and I am sure our research paths will cross again.

To our industrial partners; Lars Strandén at SP and Niclas Nygren and Hossein Zakizadeh at Volvo Technology, thank you for the great collaboration and encouragement throughout.

Finally, thank you to my parents and to Jenny for supporting me throughout, and to Eleonora; hopefully my work will make the world you inherit a little bit more cooperative.
List of publications

The publications appended to this thesis are as follows:


VI K. Lidström and T. Larsson, Enabling Adaptation in Cooperative Vehicles by Mapping the Radio Environment, Submitted for journal review, October, 2011

Related publications by the author:

• K. Lidström, J. Andersson, F. Bergh, M. Bjäde and S. Mak, ITS as a tool for teaching cyber-physical systems, Proc. of the 8th ITS European Congress, Lyon, France, June 2011

• A. Böhm, K. Lidström, M. Jonsson, and T. Larsson, Evaluating CALM M5-based vehicle-to-vehicle communication in various road settings through field trials, Proc. of the 4th IEEE LCN Workshop On User MObility and VEhicular Networks (ON-MOVE), Denver, USA, October 2010

• K. Lidström, On Strategies for Reliable Traffic Safety Services in Vehicular Networks, Licentiate thesis, School of Science and Technology at Örebro University, April 2009

• K. Lidström, Cooperative Safety Based on Shared Conventions, Poster at the 2nd European Road Transport Research Arena (TRA 2008), Ljubljana, Slovenia, April, 2008


Awards and recognitions related to the thesis work:

• Second place in the Grand Cooperative Driving Challenge (GCDC), as leader for the Halmstad University team, for an implementation of a cooperative platooning system, Helmond, The Netherlands, May, 2011

• First prize in the CVIS application innovation contest for an implementation of a cooperative pedestrian crossing system at the 16th World Congress on ITS, Stockholm, Sweden, September, 2009

• First prize for the poster “Cooperative Safety Based on Shared Conventions” in the Young European Arena of Research competition at the 2nd European Road Transport Research Arena (TRA 2008), Ljubljana, Slovenia, April, 2008
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Chapter 1
Introduction

The vision of cooperative vehicles, coordinating themselves through wireless information exchange, promises a wide range of new services for increasing traffic efficiency, safety and comfort. Applications such as intersection collision avoidance, cooperative adaptive cruise-control and road-condition warnings are all dependent on, or can benefit from, wireless information exchange.

Cooperation is envisioned not only to take place between vehicles but also between vehicles and the infrastructure. Traffic lights that communicate their signal timings could for example allow drivers to better adjust their speed, avoiding unnecessary stops and lowering fuel consumption.

Although the vision of wirelessly communicating vehicles can be traced back almost to the dawn of the modern automobile [15] it has recently attracted an increased interest. Standardization of inter-vehicle communication technologies and dedicated frequencies around 5.9 GHz as well as the ability to integrate into vehicles communication and computation devices in a cost-efficient manner have been driving forces in this development. On a more general level, information exchange between vehicles has several advantages:

- **Extended situational awareness**: Perception is, ideally, not limited by line-of-sight as with traditional in-vehicle sensors (e.g. radar and cameras)
- **Information redundancy**: Observations from multiple nodes can be combined when constructing a model of the surroundings.
- **Simplified sensing**: Cooperative objects can communicate their identities as well as properties that may be impossible to sense externally, e.g. the weight of a vehicle.

However, enabling distributed coordination of vehicles through the use of wireless communication also leads to a number of new challenges:

- **Unreliable communication**: The wireless link between nodes can be affected by a number of disturbances outside the control of the system, for
example physical obstacles and multi-path fading. High node mobility also leads to a volatile network topology.

- **Decentralized coordination**: Lack of centralized infrastructure has effects on several levels. On the lower levels nodes must share the wireless medium without centralized arbitration while ensuring that safety-related messages will eventually be transmitted. On a higher level the task is to monitor and coordinate vehicles and drivers to achieve safe, efficient and comfortable traffic.

- **Interoperability**: Both at physical layers, e.g. link layer, and at higher layers nodes must be able to communicate with each other. Standardization plays an important role in harmonizing communication technologies and messaging formats.

- **Security**: Decisions made by the in-vehicle system that are based on information received from other nodes opens up for attacks on the system, for example malicious nodes transmitting fake data. Privacy issues might also arise, for example if it becomes possible to track the location of a vehicle based on the messages it sends.

Previous work has to a large degree dealt with the first two challenges by contributing solutions on the link and network level. Our work is motivated by the lack of results addressing the first two challenges on the middleware and application level; results which we believe are necessary for the robust operation of cooperative services.

### 1.1 Problem Formulation

Whereas current active safety systems rely on highly local environmental information, such as radar targets immediately in front of the vehicle, a cooperative system has a much wider perceptive range. An expanded environmental perception, and the ability to explicitly coordinate with other vehicles, requires coordination models that go beyond the basic short-term kinematics models often used today. For coordination tasks with a longer time horizon driver control input and driver intentions, dependent on environment features such as road geometry and conceptual features such as traffic rules, play a larger role.

In relation to the challenges, **decentralized coordination and unreliable communication**, we investigate the following two research questions.

- How can models describing the interaction between the driver and road geometry, traffic signal infrastructure and other traffic participants be implemented and how effective are they in predicting the evolution of the traffic state?
1.2 Contributions

The results of this thesis attempt to answer the first of the two research questions by showing that it is possible to detect hazardous traffic situations by mimicking the coordination strategies of human drivers through pre-shared models of normative behavior. We have shown how such pre-shared models can be expressed and how warning criteria based on observed behavior in relation to the models can be formulated.

The second research question is addressed by showing how communication disturbances caused by static phenomena can be recorded, in what is referred to as a radio map, and used to predict future communication performance. Our contributions in this area include experimental measurements of communication performance in urban and rural scenarios as well as methods and algorithms for collecting, aggregating and distributing radio maps. We propose both an in-network method, requiring no infrastructure support, as well as an infrastructure-based method. Furthermore, we also identify the need for an application requirements specification with which the radio map can be compared. We propose such a specification by extending a performance metric proposed in literature, T-Window reliability, with a context-dependent coverage component.

The following specific contributions have been made in relation to the first research question presented in the previous section:

- An in-vehicle system architecture for cooperating vehicles identifying the need for reliability support functions at the middleware and application layers (Paper I).
- Evaluation of the feasibility of predicting driver intent by observing only vehicle kinematic state and position relative to road geometry. Experimentally evaluated using vehicle traces extracted from a video recording of an intersection (Paper II).
- A driver-behavior monitoring application and warning criterion that takes multiple driver intentions into account. Evaluation of the criterion is performed using recorded mobility traces (Paper III).

In relation to the second research question the following contributions have been made:

- A communication monitoring method using in-network aggregation of communication observations. Evaluation of the method through simulation (Paper IV).
• A requirements format enabling the application designer to express requirements on communication quality and coverage for cooperative traffic applications. (Paper V)

• A communication monitoring method using centralized aggregation of communication observations in conjunction with a method of comparing the communication requirements specification to the resulting radio map. (Paper VI)

Additional contributions to the field of cooperative traffic systems have been made by the author in related publications and demonstrators included as references to this thesis:

• A cooperative adaptive cruise control (CACC) system implemented in a Volvo vehicle for participation in the Grand Cooperative Driving Challenge, a competition in cooperative platooning [21]. 5.9 GHz vehicle-to-vehicle communication was employed in order to create a control system for regulating the speed of the ego vehicle based on information received from vehicles ahead. The system was judged as second best in competition with eight other research institutes. Participation in the competition served to strengthen ties within the European cooperative traffic research community as well as to publicly showcase the state-of-the art of the field.

• Measurement campaign to explore 5.9 GHz packet-drop characteristics in urban, highway and rural non-line-of-sight scenarios (section 2.2 and [6]). The author was principally responsible for the implementation of the measurement system and 3D visualization of measurement data, as well as part of the data collection task. The measurements provide insights into the effect of non-line-of-sight propagation characteristics due to static obstacles on high-level communication quality.

1.3 Approach

The results presented in this thesis have been reached using various approaches. Focus has been put on testing proposed methods by implementing and deploying artifacts in real world settings.

• An initial literature survey, conceptual framework and system architecture was developed in Paper I to serve as a roadmap for the thesis work.

• Measurement campaigns using vehicles instrumented with inter-vehicle communication were performed to investigate the effect of non-line-of-sight conditions on communication performance.

• Computer simulations were performed of communication environment monitoring where network scale precluded real world experiments.
• Functioning implementations, demonstrators, were developed to evaluate proposed coordination approaches.

1.4 Outline of Thesis

The thesis is outlined as follows. In Chapter 2 we give an overview of how cooperative traffic systems are motivated from four perspectives; vehicle safety, infrastructure and efficiency, autonomous vehicles and traveller information. A short review of radio propagation phenomena and their effects on inter-vehicle communication is also made. Chapter 3 outlines the strategies found in the attached papers on increasing the robustness of cooperative traffic systems. In Chapter 4 related work is presented. Summaries of the attached papers are given in Chapter 5 and finally conclusions and future work are presented in Chapter 6.
Chapter 2
Background

2.1 Motivations for cooperative traffic systems

In this section we give a wider background to cooperative systems in the transportation domain through four perspectives. The first is the use of cooperative technologies in vehicle safety systems to combat limitations of current sensor technologies. The second is from the macro perspective, where the aim of infrastructure providers and traffic management organizations is to improve the efficiency of the transport system as a whole. The third perspective is a glance into the future of road transport, the evolution of autonomous vehicles. Finally the entry of personal mobile devices into the transportation domain is touched upon.

2.1.1 Wireless communication: the next step in vehicle safety

Personal mobility is a key contributor to high quality of life, symbolized perhaps strongest by the automobile and the freedoms it gives. At the same time the number of people killed in traffic across the globe each year is estimated at almost 1.2 million [1], in the European Union (EU27) alone in 2008 more than 38,000 people lost their lives [14]. Although the trend is toward decreasing fatality rates in regions like Europe, road accidents are projected to go from being the ninth to being the fifth leading cause of death globally in 2030 [31].

In addition to the personal tragedies the societal costs attributed to traffic accidents are significant:

“Road crashes in the EU each year lead to 97% of all transport deaths and to more than 93% of all transport crash costs and are the leading cause of death and hospital admission for citizens under 50 years. Road crashes cost more than congestion, pollution, cancer and heart disease and result in a five times higher death rate in the worst than the best performing Member States.” [10]
Wireless communication between vehicles for traffic safety can be viewed in the context of vehicle safety evolution over the past decades. One categorization of vehicle safety systems considers when they are applicable in relation to a crash event (as proposed by Haddon [16]); before the event, (pre-crash), during the event, (crash), or after the event, (post-crash).

Figure 2.1: Examples of vehicle safety systems categorized according to when they are applicable in an accident scenario. Cooperative safety systems chiefly address the pre-crash phase.

Modern vehicle safety solutions stem to a large degree from the extensive research into the crash phase, which has yielded highly effective safety measures. Increased vehicle crashworthiness is an important factor in the reduction of injuries and fatalities caused by traffic accidents [34]. Passive safety, which focuses on mitigating the consequences of an accident during the crash phase, includes protecting occupants through the mechanical design of the vehicle as well restraint and impact protection devices such as seat-belts and air bags.

In the pre-crash phase active safety systems support the driver in order to mitigate or even avoid the accident. Active safety systems thus aim to address the factors that cause accidents, of which many can be classified as being due to driver error [5]. Examples include electronic stability control (ESC) and anti-lock brakes (ABS) that assist the driver in maintaining control of the vehicle. Whereas ESC and ABS relies on sensor data describing the state of the ego vehicle only, the current generation of active safety systems include information also about the surroundings of the ego vehicle. Using sensors such as radar, lidar and cameras to perceive the environment, functions such as automatic braking can be realized that intervene in order to avoid collisions with obstacles or other vehicles.

The traffic environment can be highly complex and perceiving it using on-board sensors is fraught with uncertainty. For example, a collision avoidance system based on radar must be able to correctly classify and track targets that may come to be in the path of the ego vehicle while at the same time rejecting clutter. Fusing multiple types of sensor input is commonly used to reduce the uncertainty, for example by combining the radar input with a camera-based target classifier improved results can be achieved [2]. Another limitation with commonly used on-board sensors, which is more difficult to address by adding further on-board sensors, is the line-of-sight (LOS) requirement. As part of their principle of operation radar, lidar and cameras cannot in general see through targets or behind obstacles. At intersections, the correlation between restricted
sight distance of the driver and accident risk have been shown [35] and in such scenarios LOS sensors are of limited use.

Wireless inter-vehicle communication offers an attractive solution to both the perception uncertainty and non-line-of-sight problems in an active safety system. Vehicles that transmit information about themselves allow for a significant increase in environmental perception by other vehicles. Not only can the unique identity, location, speed and heading be communicated but also information about other characteristics can be sent that cannot be detected by sensors in other vehicles. A hazardous goods transport could for example transmit information about the type of cargo it is carrying or information about its expected braking distance given the cargo weight.

Furthermore, environmental perception using wireless radio communication is also envisioned to be more robust against non-line-of-sight conditions (although this depends to a great deal on the radio technology used). Retransmission strategies also make it possible to relay information via intermediate nodes, offering the ability to route messages around obstacles.

A fundamental limitation of cooperatively sharing information via radio is that non-cooperative objects (objects that are not radio-equipped) cannot participate in the information exchange. Thus, cooperative traffic safety should not be seen as an alternative to systems based on on-board sensors but rather as a complement. In fact, although wireless communication between vehicles allows for highly complex coordination, from an active safety viewpoint wireless communication is often considered as simply a range extension of the on-board sensors. Such an approach allows for simplified interaction protocols between vehicles, often limited to periodic transmission of messages containing the kinematic state of the vehicle. Periodically transmitted state information messages are referred to using varying terminology, for example beacon messages [32], heartbeat messages [38] and cooperative awareness messages [13]. We choose to adopt the cooperative awareness message (CAM) terminology in the remainder of this thesis.

The contributions of the thesis to the area of cooperative traffic safety are manyfold. The use of pre-shared normative behavior models directly addresses the design of safety applications that aim to detect hazardous situations related to road-geometry, such as swerving or not stopping for a red light. Our proposed communication quality requirements format allows application designers to explicitly formulate requirements on message inter-arrival times and coverage. In combination with the proposed radio environment mapping and monitoring method this enables adaptation strategies to be included on the application level. To our knowledge it is the first time that a context-dependent communication coverage specification has been proposed for cooperative traffic systems.
2.1.2 Increased efficiency, the infrastructure perspective

Not only the vehicles themselves but also the road infrastructure plays a critical role with regards to both traffic effectiveness and safety. As the number of vehicles on our roads increases the strain on existing road infrastructure also increases, with consequences such as lost productivity and increased pollution. If this trend continues, advances in reducing individual vehicle emissions risk being offset by increases in congestion and commuting times [22].

In many cases it is prohibitively expensive, if even possible, to expand the infrastructure to accommodate the increase in traffic volume. Thus, significant effort has been put into improving the performance of the existing infrastructure by introducing various forms of information and communication technologies (ICT), collectively referred to as intelligent transportation systems (ITS).

Examples of intelligence within the infrastructure include sensing capabilities such as loop detectors in the roadway, camera-based traffic flow monitoring, licence-plate recognition and transponders for road tolling. Influence, or actuation, on the traffic environment can be performed for example through ramp metering, traffic light preemption and variable message signs.

Wireless communication from infrastructure to vehicles is already in use today. Often it is centralized in nature and broadcast to a larger geographic area, such as voice traffic updates via FM radio or data updates via RDS-TMC. Direct vehicle-to-infrastructure communication is mainly found within the road-tolling and congestion charging domain, based on dedicated short-range communication (DSRC) systems. Road-tolling DSRC systems are typically based on transponders that transmit data elicited by readers located in gantries above the road. Although such transponder tags (both active and passive) can be produced at low cost, their range is limited and they are dependent on readers to function.

In contrast, continuous wireless communication between individual vehicles and the infrastructure could enable new ITS services by moving the intelligence (and the cost of the system) into the vehicles themselves. Continuously communicating vehicles can also be used as probes in order to gather so-called floating car data, for example information about the average speed for a given road segment. The floating car data can then be used as input to traffic models in order to gain a real-time view of the traffic flow.

From a traffic safety perspective communication between vehicles and infrastructure can also offer new types of services. One example from our previous work is a cooperative pedestrian crossing application [23]. The application uses 5.9 GHz wireless communication integrated into the infrastructure of a signalized pedestrian crossing to transmit traffic light status and whether a pedestrian has requested to cross to approaching vehicles. By monitoring the driver behavior the in-vehicle part of the system can broadcast warning messages if it detects that the driver is not stopping for the red light. Depending on the state of the traffic lights the result of such warning messages could be to
extend the pedestrian light red phase in conjunction with in-vehicle warnings to the driver.

From the road operator perspective, the long term vehicle-to-vehicle communication map building proposed in this thesis offers the ability to plan deployment of road-side units and to evaluate already deployed communication infrastructure. Furthermore, using regular vehicles as probes reduces the cost of such measurements to the cost of providing the centralized aggregation infrastructure.

2.1.3 The vision of autonomous vehicles

Vehicles that drive themselves has been a long-standing vision, already in the 1939 World Fair Futurama exhibit, General Motors’ vision for highway transport in the future of 1960 included maintaining safe distance between vehicles “by automatic radio control”. More recently projects such as California PATH have realized demonstrators where cooperative autonomous vehicle behavior was shown in several scenarios [42].

Further steps from autonomy in well-defined environments toward vehicles driving themselves through unknown terrain and urban environments were taken as part of a series of challenges held by DARPA in 2004, 2005 and 2007.
The focus in the DARPA challenges was on environmental perception solely using on-board sensors which was a testimony to the fact that the vision centered around technology for deployment in “non-cooperative” environments.

In more typical (civilian) scenarios self-driving vehicles can benefit from an increase in perceptive range using wireless communication in much the same way as active safety systems can. However, using wireless communication higher levels of information exchange can also be performed which makes joint coordination of multiple self-driving vehicles possible.

Figure 2.3: Cooperative platooning during the 2011 Grand Cooperative Driving Challenge is an example of multi-vehicle coordination using wireless communication. The Halmstad University vehicle is number 4.

Our contribution to the 2011 Grand Cooperative Driving Challenge (GCDC) is an example of how wireless communication can be used to coordinate semi-autonomous vehicles (Figure 2.3 and [21]). In the GCDC vehicles utilized both periodically transmitted messages containing state information as well as an on-demand message set for joining and leaving groups of vehicles travelling together, a so-called platoon. Through the use of wireless communication a cooperative adaptive cruise-control (CACC) system can be realized allowing vehicles to follow each other automatically in a safer and more efficient manner than by only relying on on-board sensors (such as a radar-based adaptive cruise-control system).

2.1.4 The connected traveller

At the same time as road infrastructure and vehicles are expected to become more “intelligent”, advances in personal mobile devices such as smartphones
and navigation units means that these devices are becoming important platforms in the transportation domain. The devices, which are associated to an individual traveller, are especially suitable for multi-modal transportation purposes.

The first generations of nomadic devices for transportation purposes were dedicated devices such as after-market dash-mounted navigation systems. Subsequent generations of these devices offered integration with the infrastructure often providing floating car data gathering capabilities, relying on already existing communication infrastructure such as cellular networks for both uploading of floating car data and downloading of traffic information.

Many of the functions once found only in dedicated devices are now integrated in more general-purpose devices such as smartphones. The extension of services offered on such personal mobile devices into the transportation domain include eliciting traffic information directly from users. This includes applications that let users share information about events in the traffic system, such as accidents or locations of speed checks, in a form of social network.

Compared to the life cycle of vehicle or infrastructure systems the life cycle of a nomadic device is considerably shorter. Advances in nomadic devices are thus expected to out-pace those of integrated systems. Providing flexible means for integrating nomadic devices and third-party software into vehicles may be a way of combining the two.

For third-party device integration the ability to formulate communication quality requirements explicitly is important. We believe that requirements specifications formats such as the one proposed in this thesis are useful when allowing third-party integration into a safety-critical system. Such a specification could for example be used as a form of admission control when integrating systems during runtime.

### 2.2 Wireless inter-vehicle communication

Several wireless technologies have been proposed and evaluated in literature for direct vehicle-to-vehicle messaging. However, for wide system interoperability the industrial and research community have identified the need for standardization. This has resulted in efforts such as the IEEE 802.11p standard (see [17] for an overview) using the recently assigned European ITS band of 5.875-5.905 GHz [8].

Radio spectrum around 5.9 GHz is also gaining ground globally for ITS applications, e.g. the U.S. 5.850-5.925 GHz dedicated short range wireless (DSRC) band [9]. It is expected that economies of scale resulting from this type of standardization will enable wide deployment of vehicle-to-vehicle and vehicle-to-infrastructure systems. Testing of DSRC communication in real traffic conditions has characterized the dependence of this communication technology on the surrounding topography, i.e. the degradation in non line-of-sight (NLOS) conditions [36].
Wireless communication between vehicles is among other things affected by the structure of the environment, the relative location of the transmitting and receiving node and their mobility characteristics. Radio signals reaching the receiver from the transmitter either travel directly between the nodes in case of line-of-sight propagation or reach the receiver after having been reflected on objects in the environment, multipath propagation. As either of the nodes move, time-varying characteristics of the channel are introduced, so-called fading. Fading that varies quickly over time, often caused by multipath reflections that interfere destructively or constructively with each other, is referred to as fast fading and even slight movements of either node causes abrupt changes in the interference pattern. Conversely fading effects that can be modeled as constant, or changing slowly, over time are referred to as slow fading, such effects are often due to shadowing caused by terrain or buildings.

Multipath propagation is typically attributed to radio waves being reflected, scattered and refracted on their way from the transmitter to the receiver as illustrated in Figure 2.4.

Figure 2.4: Multipath propagation due to diffraction, reflection and scattering.

In a vehicle-to-vehicle communication scenario NLOS conditions can be expected in many situations as transmitter and receiver antennas heights are low in relation to obstacles such as buildings. Urban intersections is a concrete scenario where a LOS component in many cases does not exist between approaching vehicles [25]. Roadway crests and dense foliage are further examples observed in our own measurements.

To gain a qualitative understanding of the effect of various types of terrain and structures on 5.9 GHz vehicle-to-vehicle communication, we have performed field trials using instrumented vehicles (for an in-depth overview see [6]). The trials show a clear correlation between NLOS conditions and increased packet drop rate for both urban and rural scenarios as shown in Figures 2.5 and 2.6. In the intersection scenarios it should be noted that packets can still be received although LOS does not exist between the transmitter and re-
receiver, due to the multipath propagation phenomena mentioned earlier. However, communication quality in terms of packet-reception rate under NLOS conditions degrades quickly as the distance to the intersection increases. The degradation is likely due to reduced signal strength at the receiver as well as interference between the various multipath components of the reflected signal.

In general characterizing radio wave propagation in a given environment is difficult. For the wavelength under consideration (around 5 cm) even small objects impact the propagation characteristics. Additionally the type of materials that make up obstacles such as buildings have an effect on radio wave reflection and absorption, making prediction of especially fast fading behavior hard. On the other hand, in situations with less contribution of multipath components the slow fading caused by obstacles such as buildings was highly reproducible in our trials.

In general, many nodes are expected to communicate using a shared wireless channel which means that strategies for when each node is allowed to transmit are needed. Multi-user channel access strategies are defined in the medium access control (MAC) layer of the communication protocol stack and regulate access to the channel through time, frequency or code division. The carrier-sense multiple access with collision avoidance (CSMA/CA) medium access strategy is used in the 802.11p standard. Using CSMA/CA, a node first listens to the channel to see if it is in use before transmitting (carrier sensing), if it is in use the node waits for a certain amount of time before trying again. A handshaking procedure is used before starting transmission using ready-to-send and clear-to-send messages for collision avoidance.

The use of CSMA/CA in vehicle-to-vehicle communications has disadvantages. This is mainly due to the fact that the back-off time introduces non-determinism into the channel access procedure in the sense that unbounded delays, although unlikely, may occur. Thus other strategies that guarantee deterministic medium access have been proposed for use in vehicular scenarios. Sjöberg et al. propose the use of self-organizing time-division multiple access (STDMA), already used in maritime and aerospace settings, for inter-vehicle communication [4].
Figure 2.5: Field trials with 5.9 GHz vehicle-to-vehicle communication for multiple runs at a road crest (top) and at a curve occluded by dense foliage (bottom). The transmitter (yellow push-pin) is static and the packet reception ratio as a function of the binned receiver location is indicated by the bars (PRR=1 is indicated by tall green bars and PRR=0 by short red bars.) (©Google, Map Data ©2010 Lantmäteriet/Metria used with permission I210/0061)
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Figure 2.6: Field trials with 5.9 GHz vehicle-to-vehicle communication in an urban scenario with varying transmitter position. The transmitter (yellow push-pin) is static and the packet reception ratio as a function of the binned receiver location is indicated by the bars (PRR=1 is indicated by tall green bars and PRR=0 by short red bars.) (©Google, Map Data ©2010 Lantmäteriet/Metria used with permission l210/0061)
Chapter 3
Situation-aware vehicles

In this Chapter we describe how the appended papers relate to the two challenges introduced in Chapter 1. In Section 3.1 the contributions of Paper II and Paper III regarding awareness of the traffic environment is considered and how, by extending the perceptive horizon, wireless inter-vehicle communication requires an extended traffic environment prediction horizon. Section 3.2 gives an overview of the contributions in Papers IV-VI on how awareness of the communication environment can be introduced and utilized in a cooperative traffic system.

3.1 Awareness of the traffic situation

Systems that analyze and act on environmental information gathered from vehicle-mounted sensors in order to predict and avoid hazardous situations, such as collisions, already exist in modern automobiles. A common feature of these functions is that they are predictive in nature, applying models to generate hypothetical future situations from the gathered information onto which hazard criteria can be applied. In part due to limitations in the range of onboard sensors the predictive horizon, the number of time steps into the future for which the prediction model is applied, is typically short.

A key characteristic of cooperative traffic systems is the extended perceptive range enabled by wireless communication. In-vehicle systems that analyze the environment around the vehicle suddenly have information not only regarding obstacles within line-of-sight but also about traffic participants hidden from sight. In theory, using multi-hop communication, the perceptive range can become virtually unlimited as information is relayed from one location to another. Even when only considering single-hop communication the typical radio range in ideal situations is several times greater than that of commonly used sensors such as radar.

To make use of the extended perceptive range hazard detection algorithms are needed that are able to reason about the traffic situation further into the
future compared to the algorithms in use today. It is clear that as the predictive horizon is extended, other factors than those commonly modeled influence the evolution of the traffic state. Consider for example an algorithm used to pre-tension seat-belts when a crash with another vehicle is imminent. In this scenario the prediction horizon is short, most likely sub-second, and the models used to predict the state evolution can be limited to dealing with the Newtonian mechanics of the ego and target vehicles. In contrast, consider a cooperative intersection collision avoidance application which uses as input information about approaching vehicles several seconds away from the intersection. Over a prediction horizon of several seconds driver input greatly influences the state evolution. Driver input in turn is affected by elements of the traffic environment such as traffic signal infrastructure, road geometry and other traffic.

In contrast to equations describing the mechanics of vehicle motion, modeling the interaction between the driver and the traffic environment requires modeling both discrete and continuous aspects. Examples of discrete elements that affect driver behavior is the state of traffic lights and road regulations such as right-of-way. However, abstractions geared towards discrete modeling and reasoning become cumbersome when continuous aspects need to be included, it is for example not enough to state that a driver must brake for a red light but also what the deceleration profile should look like. Thus we have attempted to capture both discrete and continuous aspects in our work.

In Paper II we attempt to use models of driver interaction with road geometry and other traffic participants in order to predict the evolution of vehicle trajectories in an intersection. Our models include a geo-referenced graph of road segments and their connections as well as models that describe acceleration behavior when turning and when following another vehicle. Models such as the ones used can be feasibly generated for a multitude of traffic situations using pre-existing data sources, such as digital road maps and car following models, but can also be learned from observing the behavior of traffic participants. However, as the models are used within the framework both for predictive and corrective purposes, there is a risk that basing them solely on observations of actual driver behavior may lead to models describing hazardous (but common) behavior. With regards to generating models describing the interaction between the driver and the road infrastructure there is a need for higher fidelity digital road maps that describe not only road but also individual lanes and locations of elements such as traffic lights and pedestrian crossings. On-going efforts in automatic mapping the roadway environment, such as Google Streetview, indicate that maps of sufficient detail are likely to be available.

Although the models used in Paper II are deterministic, reasoning about the future is fraught with uncertainty. Not only are the models only approximations of the expected behavior in a given situation, input in the form of vehicle locations and other properties also contain uncertainties caused by sensor limitations. Thus, the framework chosen to evaluate observations against models is particle filters, which allows sequentially combining observations and gen-
3.2 AWARENESS OF THE COMMUNICATION ENVIRONMENT

Generating a discrete probability distribution over potential future maneuvers. We show that the proposed models can be effectively used to accurately predict whether a driver will pass through the chosen intersection or make a turn.

Following the line of investigation initiated in Paper II a generalized hazard detection criterion is presented in Paper III. The criterion is based on the observation that situations where the maneuver probability distribution is flat, i.e. where no modeled maneuver is more likely, may be indicative of hazardous situations. The criterion is further extended to also include situations where the most likely maneuver switches rapidly, indicating an unpredictable and possibly hazardous driver. The road geometry models in Paper III are extended from the one-dimensional lane representation used in Paper II to a two-dimensional representation using artificial potential fields. This was due to the limitations observed in Paper II when trying to infer turning intent as the lateral positioning of the vehicle is a key predictor. Artificial potential fields offer the ability to model the combined effect of several elements in the traffic environment by superimposing fields. In the scenario explored in Paper III braking behavior for a traffic light is combined with lane-following behavior.

The specific framework chosen, particle filters, are an efficient way to sequentially integrate observations with process models that are non-linear as is the case in Paper II and Paper III. However, to achieve acceptable performance the computational resources needed for particle filtering may become a limiting factor, especially if deployed in a resource-constrained embedded automotive setting.

The mentioned uncertainty arising from limitations in sensor ability also apply to observations received via wireless communication. When performing the filtering process accurate estimates of observation noise improve the output quality. Thus, the ability to predict not only the traffic environment but also the performance of the sensing abilities themselves is important. In the following section we address the second theme of this thesis, monitoring and predicting the performance of the defining aspect of cooperative vehicles, the radio communication environment.

3.2 Awareness of the communication environment

In a cooperative traffic system the wireless exchange of information between traffic participants is the base of a range of new functions. For many of these functions the wireless communication is a requirement and it is not possible to achieve similar functionality using only on-board sensors. The communication technology studied in this thesis, direct vehicle-to-vehicle communication at 5.9 GHz, enables many of these new functions but it also introduces new types of failure modes into the system.

For a line-of-sight sensor such as radar or lidar the lack of a return signal implies that there is no target within the sensor range. A significant difference when using radio communication to sense the environment is that a lack of
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Signal does not necessarily imply that a cooperative node is not present, it may simply be that wireless communication is impossible between the two nodes. Signal degradations caused by non-line-of-sight between the ego vehicle and another cooperative node may lead to such communication failures as was shown in Section 2.2. The work presented in Papers IV-VI aims to provide a mechanism for reasoning about the likelihood that communication between locations will succeed, focusing on the types of disturbances caused by static obstacles such as terrain or buildings.

Practically such a mechanism can be implemented as a monitoring component to which general-purpose applications can interface. The monitoring component is responsible for detecting faults and communicating these to subscribing applications, which in turn adapt their own behavior in response. An in-vehicle software architecture outlining the use of such a monitoring component is presented in Paper I.

In order for the monitoring component to decide whether an application needs to be notified of a communication fault, a description of the required communication quality must first be registered. The definition of when a communication fault has occurred depends on the requirements of the individual application. For example, a low-criticality application may accept a higher proportion of dropped CAMs than a high criticality application.

Since CAM transmission is periodic and dropped CAMs can often be estimated due to the inherent redundancy of the transmitted information, the CAM inter-arrival time becomes a key quality metric. We further identify the need for including traffic environment information when reasoning about required communication quality. Since cooperative in-vehicle applications typically take as input the location and movement of vehicles in the vicinity and produce as output recommendations or control output to alter the future state of the physical environment they can be considered as “situated” applications. Thus, requirements on communication performance concern not only how well one must communicate but also with who, and by extension where, one must communicate with. We refer to the where part of the requirements specification as the required coverage.

The required coverage for cooperative traffic applications has several characteristics which set it apart. It is dynamic as it is dependent not only on the ego vehicle behavior but also the traffic environment, such as roadway infrastructure. For example, an intersection collision avoidance application requires communication with vehicles approaching the intersection on relevant road segments. The same application may have virtually no requirements on communication coverage when travelling on a freeway. Similarly, an application concerned with warning the driver of sudden traffic jams requires communication coverage farther ahead when the ego vehicle is driving at high speed compared to when it is standing still. In Paper V we propose that such coverage requirements can be formulated as rules for selecting road segments from a digital road map. The rules are constructed using common set theoretic operators and spe-
cialized functions that allow road segment selection based on relative distance from the ego vehicle, as well as road segments expected to be travelled on by the ego vehicle (thus enabling speed-dependent selection).

Given a description of the required communication quality in terms of coverage and maximum CAM inter-arrival time, the monitoring component requires a model of the communication environment to evaluate it against. Such models are typically of a more general nature, describing the characteristics of a class of environment, for example the expected transmission range in urban, rural or indoor settings. However, such models have a too high level of generality when the requirement is to predict the communication quality at a specific intersection.

The types of prediction necessary for cooperative traffic use, taking into account detailed characteristics of the environment such as terrain and buildings are referred to as site-specific. Site-specific propagation modeling is frequently used in the special, but common, case where one of two communicating nodes remains static such as is the case for base stations in a cellular network, or access points in a wireless LAN.

Methods similar to the use of ray-tracing in computer graphics can be utilized in propagation modeling by calculating the properties of a number of rays, emanating from the node of interest, as they reflect off of objects in the environment. A drawback with this approach is that representations of obstacle geometries have to be maintained for the specific site, which effectively limits how detailed the propagation modeling can be made. Updating such representations as the environment changes also limits this approach to either coarse grained information or small geographical areas.

Instead, our proposed approach is to utilize the vehicles as mobile probes to measure communication performance between various locations in the traffic environment. Such measurements can take place during normal operation of the vehicles. As a mapping approach assumes that historic observations can be used to reason about future performance we expect that mainly relatively static communication disturbances can be reliably recorded. Slow fading such as shadowing by buildings or terrain is an example of disturbances that is likely to be present over time for a given pair of locations, as observed in our measurement campaigns. Dynamic disturbances such as destructive interference due to multipath propagation, or shadowing caused by moving objects such as other vehicles, are difficult to detect using past observations.

Another factor that affects the ability to use historic observations to predict future performance is that nodes themselves may have unique characteristics, such as varying antenna heights, that affect communication performance. Such dissimilarities can be addressed technically, for example by creating multiple strata in the communication map depending on the class of vehicle using it. However, one can also argue that maximizing not only the performance but also the predictability of inter-vehicle communications should be a goal of ongoing standardization efforts. Parallels can be drawn to the design of current
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visible-light communication systems, such as headlights and brake lights, that are heavily regulated in the automotive domain.

Using a mobile probe to measure communication characteristics as a function of location is common in settings where one node is fixed, such as a cellular tower or a wireless access point. When one node is fixed the resulting measurements can be seen as a map describing the measured communication quality for various locations of the mobile probe. In a scenario where measurements are performed in a network that lacks fixed infrastructure a measurement is valid only for specific locations of the transmitter and receiver. In an unconstrained environment the number of possible combinations of transmitter and receiver positions is naturally very large, however in a vehicular scenario there are limiting factors that can be exploited.

Two main factors limit the possible size of the radio map. The first is the restricted mobility model of vehicular traffic, vehicles typically travel on roads which significantly reduces the number of location pairs that need to be considered. The second factor is the relatively short range envisioned for vehicle-to-vehicle communication, typically below 1000 m. Combined, the two factors significantly reduce the number of observations necessary to map an area.

Another aspect is whether aggregation of communication observations takes place distributed in the network or with the aid of centralized infrastructure. In Paper IV we propose a distributed mechanism that does not rely on additional infrastructure. Besides the independence of infrastructure, in-network aggregation also offers quick updates which allows for detecting disturbances with shorter time duration, for example semi-dynamic obstacles such as parked vehicles. However, the proposed aggregation mechanism relies on the availability of nodes to route observations via, which may not be possible in sparse traffic. Furthermore, the aggregated data about a specific location is only stored within the nodes taking part in the aggregation and is effectively lost if those nodes leave the network, which makes long-term mapping and collection of large sample sets complex.

Centralized aggregation, as proposed in Paper VI, requires dedicated communication to the aggregation point but allows for a much simplified collection and aggregation procedure. Long-term storage of observations is also made possible. A further advantage of centralized aggregation is that situations in which vehicles were not able to communicate at all can be detected. By simply knowing that two vehicles were within transmission range at the same time but did not log having received a CAM from the other such situations can be detected.

The final step is to adapt system behavior in response to a notification from the monitoring component that requirements cannot be met. Adaptation strategies include application-independent measures at multiple levels of the communication stack, such as changing CAM transmission interval, utilizing multi-hop routing and vertical carrier hand-over. While adaptation below the application layer may be sufficient for some application classes, we envision that applica-
tion specific adaptation schemes are also necessary. For example, consider a safe speed advisory application that recommends drivers to drive slower than the posted speed limit in high risk areas such as school zones. Adaptation at the application layer can in this case mean including inter-vehicle communication performance when assessing the risk level for an area, resulting in a lowered recommended speed when approaching locations where poor communication has been observed.
Chapter 4
Related work

The system architecture proposed in Paper I contains a fusion component referred to as a context database responsible for storing and aggregating information about the environment. More generally a system for driver assistance must be able to perceive the environment in order for the system to correct driver mistakes or warn about hazardous situations. As such, advanced driver assistance systems belong to a more general class of systems that observe the physical environment through one or more sensors, analyze these potentially conflicting observations and then decide on a proper output.

In parallel to our proposal of a context database other researchers in our field have also come to similar conclusions, such as in the European SAFESPOT project where a similar repository is referred to as a local dynamic map (LDM) [33]. Zennaro et al. suggested a state map to hold common information to be used by intersection safety applications [44].

The idea of generating a fused world model separate from the applications intended to act upon it has long been an active topic in e.g. robotics, one such approach being the occupancy grid [12]. The occupancy grid is a discretized map of the environment where the probability of each discrete spatial cell being empty or occupied is maintained. Each cell can then be updated using Bayesian statistics which allows for multi-sensor and multi-robot fusion.

Although most equivalents of a context database focus on representing physical properties of the environment there are in general no limits on what types of information that can be included. Zhao et al. propose the radio environment map (REM) [45], a variant of a context database dedicated to representing information relevant to a cognitive radio system. In contrast to our radio mapping technique the REM use-case focuses on dynamic spectrum allocation in networks with fixed infrastructure whereas our contributions are to fixed-frequency quality monitoring in networks where both transmitter and receiver are mobile.
4.1 Communication awareness

Cognitive radio, as introduced by Mitola [28], introduces awareness of the environment from the wireless communication perspective. By taking into account factors that affect wireless communication, radios can adapt their operation in order to improve performance. The notion of software defined radio, where functions previously implemented in hardware instead become software parameters, theoretically enables a cognitive radio to change even its low-level functionality on-the-fly. Although the original definition of cognitive radio was quite broad a large proportion of the current literature focuses on using cognitive radios to more efficiently utilize the wireless spectrum. This is motivated by the fact that as more devices and applications become wireless, available frequency bands are becoming congested while large portions of reserved spectrum remain under-utilized. Spectrum-scavenging cognitive radios could be made to exploit available frequency bands if they can guarantee that the primary users of a frequency band can still function as intended.

Quality awareness and learning about the environment is however still a key component of the cognitive radio definition and Mitola gives examples of how awareness of radio propagation characteristics can be utilized to improve service delivery to the user [29]. The proposed radio knowledge representation language (RKRL) enables radio cognition by allowing relations between a large number of concepts relevant to radio behavior to be expressed.

The cognitive radio concept covers a broad range of tasks to be performed by an intelligent radio, sometimes blurring the border between what can be considered belonging to the application layer. In a more traditional architecture a stricter division between functions is typically made. Dividing networking functionality into layers forming a networking stack goes back to the OSI model and enables modular development and combination of protocols. However, the advantages of modularization through a stacked architecture come at a price, a protocol in one layer is unable to observe parameters in other layers that may be useful in improving its own performance. Allowing such information to flow between layers is sometimes referred to as cross-layer design and allows optimizations to be made that would otherwise not be possible. For example Sofra et al. [41] use per-packet signal strength collected over time in conjunction with statistical radio propagation models to reason about the future state of the channel which is then used as input to the routing layer. Routing protocols have been proposed that take link reliability into account based on associativity between nodes [43], i.e. where link stability has been observed, and signal strength [11], enabling classification of weak and strong links. These protocols were shown by the authors to lower the total number of link and path failures in mobile ad-hoc networks. Due to their generality, these protocols only consider properties of the network itself without taking into account additional context information such as node location. Compromising on the isolation provided by a layered architecture can lead to adverse effects such
4.2. MODELING APPLICATION REQUIREMENTS

A common property of the information stored in a context database is that it often has a spatial dimension, such as the location of a vehicle in the LDM or the boundary of a radio spectrum regulatory zone in the REM. Location aware systems have been extensively explored in the area of context aware computing [7], which cooperative traffic systems can be viewed as belonging to. A collision-avoidance application naturally needs to be aware of at least the physical context it is operating in such as the location and movement of nearby vehicles. The application might also have to be aware of the user context such as if the driver has already detected a hazardous situation. As we show in this thesis there is also a need for awareness of the communication context. Although modern sensing and cooperating vehicles can be said to belong to the class of context aware applications the term is more often used to describe applications that have been augmented with context awareness to improve some original, non-context aware, function. For example a web browser that utilizes the users current location to display information in a different way or a in-vehicle phone system that holds calls depending on the complexity of the traffic situation. Perhaps due to the user-centric connotations of the early definitions of context aware computing [39], pure control systems (such as ABS or ESC) are seldom included in the definition, although they share many of the defining characteristics.

4.2 Modeling application requirements

The QoS description mechanism proposed in paper IV allows for providing a description of application requirements on communication coverage and quality. Comparison of the QoS specification with a radio map is offered as a common service to all applications, removing the need for including this functionality at the application layer. Formulating resource requirements demands formalisms that are able to express concepts relevant to the application domain, commonly targeted resources include computation, storage and network.

Evaluation of the resource requirements against monitored or predicted resource availability is often delegated to a dedicated monitoring component. Adaptation middleware enables applications to be built and integrated into a framework that allows their behavior to be changed during runtime. A distinction can be made between middleware that adapts its own behavior and middleware that signals the application when requirements cannot be met.

One approach to allowing applications to express resource requirements and providing a monitoring service is made in the Odyssey API [30] which allows for negotiating resources between an application and the underlying operating system. Odyssey allows an application to specify upper on lower bounds on a resource (e.g. network bandwidth) as well as a call-back function which the operating system will use to notify the application if the resource
falls outside the bounds. The authors refer to the ability of the application to express its resource requirements as application-aware adaptation.

Adaptation at the middleware level enables re-use of adaptation strategies for multiple applications, however it requires that application-independent adaptation strategies can be devised. Literature on adaptation at the middleware level for mobile networks thus often concern adapting network behavior, such as changing routing parameters or protocols. In a CAM-based system relying on single-hop messaging there are limited degrees of freedom in changing networking parameters due to the simplicity of the protocol which further motivates the need for application level adaptation.

Meier et al. identify the need for space-awareness when proposing the VANET-specific middleware RT-STEAM [26]. Similar to our own observations, the authors motivate the need for spatial awareness by noting that requirements on communication QoS are often tied to coverage zones. The authors formulate a space-elastic model where hard real-time coverage is described as geographic zones of arbitrary shape that expand and contract depending on how well requirements can be met. However, whereas the RT-STEAM middleware concerns hard real-time requirements our quality metric T-Window reliability allows a more flexible definition, taking into account the probability of a given minimum message inter-arrival time. Furthermore we propose a coverage specification that allows modeling dynamic, context dependent, coverages.

4.3 Mapping and predicting communication quality

Empirically measuring communication quality has been extensively used in the planning of cellular networks [27]. However, manually gathering quality data at various locations through test drives is a labor intensive task.

The use of non-dedicated probe vehicles, for example taxis or buses, has also been explored to build coverage maps of cellular networks. A patent filed by Liu et al. and IBM [24] outlines how such collaboratively built maps can be used during route-planning to choose routes where communication requirements can be fulfilled. The proposed quality requirement is formulated as a threshold on signal quality and assumes a fixed base station infrastructure. Similarly, patents filed by Knauerhase et al. and Intel [20], [19], suggest aggregating local coverage maps at a central server, disseminating them to nodes in order to pre-fetch data and alert the user as degradations in communication quality are anticipated.

The common case where one of the communicating parties is static significantly simplifies how communication requirements and measurement data can be represented. In a system relying on fixed base-stations the question of where the mobile units must communicate to is already answered. Similarly, only the mobile unit location and its experienced communication quality at that location is necessary to build a coverage map. In our work, the fact that all nodes are mobile means that a quality mapping approach must record both the loca-
tion of the transmitter as well as the receiver. Furthermore, a definition of the locations to which a specific communication quality is required must also be provided.

The many possible combinations of transmitter and receiver location may lead to communication quality at pairs of locations becoming under-sampled. Models of radio-wave propagation can be used where no empirically gathered communication data is available. Simpler models of radio wave propagation do not require detailed information about the physical environment, rather such models typically describe propagation characteristics statistically for a given class of environment. If information about the physical environment is available, more detailed models of radio wave propagation can be employed to better predict communication quality in a specific situation. Punnoose et al. [37] propose a ray-tracing based propagation model which utilizes a model of the environment, including obstacles such as buildings and terrain, to calculate the predicted signal strength at pairs of locations in real time. The predicted signal strength is used to adapt routing decisions at the network layer. With highly detailed propagation modeling the computational complexity of evaluating the model as well as the detail level of the environment description become limiting factors if the evaluation is to be executed in real time.
Chapter 5
Summaries of Appended Papers

5.1 Software architecture for intelligent vehicles

In Paper I we propose an in-vehicle software architecture for a cooperative vehicle, taking into account components dedicated to increasing the reliability of the system.

At the lowest level the system observes its environment using sensors which produce a more or less distorted image of the real world. The distortions can be due to for example limited sensing granularity, e.g. sampling frequency, or noise inflicted by the environment or sensing process itself, e.g. atmospheric conditions affecting GPS signals. Thus there is a need to represent uncertainty in the observations made of the environment. In our proposed architecture a fusion component is responsible for combining observations from multiple in-vehicle sensors as well as observations received from other cooperative nodes.

By classifying observations into either primary or secondary we distinguish observations made by the own vehicle and one-hop neighbours from those received from neighbours more than one hop away. Varying trust levels can then be assigned to the two classes. Primary observations are assumed to be more trustworthy because they are either made by the own vehicles trusted sensor platform, or if they are received from one-hop neighbours they can be corroborated using additional information. Consider a vehicle reporting that it is located in front of the own vehicle, this can be verified by using sensors such as radar or cameras but merely the fact that the vehicle was within radio transmission range corroborates its report to some degree.

In Paper I we further suggest that the context database should not simply be a thought of as a blackboard for reading and writing data but that it also should allow applications to influence the fusion process. In the LDM approach applications can subscribe to certain changes of the database, however these subscriptions could also be used to indicate to the fusion stage which data
needs to be produced for a specific set of applications. This is in effect a way for applications to signal their requirements to the underlying layers which is necessary in order to allow adaptation of the communication strategy or to inform applications that their requirements cannot be met.

In our architecture, monitoring of application requirements in relation to the available resources, specifically the wireless medium, is handled by a “resource manager” component. In Paper IV we investigate how such a component for cooperatively monitoring the wireless medium in order to be able to predict communication quality can be implemented. Comparisons between the application demands on the context database with the predicted communication quality allows application functionality to be degraded in anticipation of communication disturbances.

Finally, the need for coordination of application outputs in order to mitigate recommendation and warning dissonance is identified. A simple static priority-based strategy is suggested as a baseline to which comparisons can be made of more sophisticated resolution strategies.

Paper I thus serves to set the stage for our continued work by contributing a base terminology with which to reason about cooperative traffic systems. The terminology defines key concepts and relations with regards to cooperative ability, type of cooperation, system topology, observation characteristics and failure modes. Furthermore the division of the context database component into primary and secondary partitions is, to our knowledge, a novel approach that identifies the difficulties, and possibilities, of redundant observations at an architectural level.

5.2 Traffic safety based on shared conventions

In Paper II a general cooperative warning application is outlined that uses reference driver behavior models and CAMs as a basis for generating warnings in response to hazardous driver behavior. Information about vehicle positions over time in relation to road geometry is utilized to infer which reference model, referred to as intention, that a driver is following. Inferring of intentions is formulated as a sequential Bayesian estimation problem, implemented using particle filters.

The approach is based on the observation that coordination in traffic, as it takes place between drivers already today, is fault tolerant in the sense that it does not rely on detailed or long-term communication between the participants. In this case the means for communication consist of visual observations, i.e. the driver seeing other vehicles, as well as explicit visual intention messages such as blinkers, brake lights and behavioral cues (acceleration, lane positioning etc.).

A set of shared models of behavior are likely to contribute to this coordinative ability. Each driver expects a certain behavior of other drivers in various situations, such as decelerating in order to yield and not swerving between lanes. By assuming that this set of models is similar in all nodes, the warning
mechanism can be distributed in the network in order to provide redundancy. Shared models that dictate behavior not only in relation to other vehicles but also in relation to the environment (road geometry etc.) reduce the dependency on inter-vehicle communication for coordination, cf. the traffic rule requiring vehicles to drive on a specific side of the road.

Driver behavior is modeled by describing the acceleration behavior in response to vehicles in front, using the Gipps car-following model, as well as braking behavior when preparing to turn using a control surface relating vehicle speed and time-to-turn to braking force.

An experimental evaluation was performed using vehicle position traces gathered from a video recording of an intersection. Correct classifications of path choice through the intersection was performed for 181 of 251 cases, false classification was performed in 30 cases and no classification in 40 cases. Particular difficulties were identified in differentiating between turning left and turning right at a T-junction due to the inability of the used models to describe lateral lane position.

The main contribution of Paper II, apart from the experimental evaluation, thus lies in the combination of multiple disparate models to describe various phases of driver behavior, exemplified by linking together an ad-hoc fuzzy-controller describing turning behavior with the difference equation-based Gipps car-following model.

5.3 A warning criterion based on model switching probabilities

Paper III addresses the limitations of the models used in Paper II by expressing normative driver behavior using potential fields, commonly used for robot guidance and control. Spatially referenced potential fields are superimposed on the road infrastructure so that virtual force vectors repel the vehicle from undesirable locations. The use of velocity-dependent field strengths is also explored in order to express desirable speed profiles. By grouping multiple fields distinct driver intentions can be expressed, for example driving in the right or left lane. The novelty of our approach lies in that the potential fields are used to evaluate the behavior of a human driver by describing a desired reference behavior, rather than being used to generate control signals.

Similar to Paper II particle filtering is used to assign likelihoods to driver intentions depending on how well the vehicle movements align with the specified potential fields. The fields are thus used to evaluate vehicle movement after the fact, rather than to control the vehicle as is often the case when using the method in robotics. A novel warning criterion based on the probability assigned to driver intentions is further proposed. A warning is triggered if no single intention is significantly more likely than another (i.e. ambiguous behavior) or if the most likely intention changes too rapidly.
The method is implemented and evaluated against a number of reference maneuvers collected using a test-vehicle at a signal-controlled pedestrian crossing. The experiment shows that a warning is generated in all the scenarios manually classified as hazardous and that warnings are not generated in scenarios manually classified as safe.

5.4 Cooperative monitoring of the wireless medium

By detecting differences in the received message sets of nodes within radio range of a single transmitter, locations with poor communication performance can be detected. In Paper IV comparisons between messages received directly from other nodes, the primary context are compared to one-hop relay messages, the secondary context.

The proposed approach is infrastructure-less, requiring only retransmission of the ego vehicle primary context and the existence of nodes to relay via. If no node is available for relay, a delayed transmission of the primary context can be utilized to perform aggregation when nodes come into contact. The in-network aggregation is suitable for highly localized and dynamic mapping of communication performance. However, since aggregated information is only available at a single node, long-term mapping without the use of infrastructure becomes complex. An experimental evaluation of the proposed monitoring approach was performed through simulation of an intersection scenario. In the simulation, vehicles approaching the intersection are unable to communicate directly and rely on messages relayed via nodes leaving the intersection to detect the communication anomaly.

The simulation shows that the existence of nodes to relay via significantly improves the performance of the approach, however at increasing network density medium-access collisions have an adverse effect. Interestingly, although the detection mechanism has a potential to detect also MAC congestion phenomena, its reliance on in-network aggregation can make this difficult in dense traffic. In other words, detecting communication disturbances in-network relies on the fact that these disturbances are not severe enough to hinder aggregation radio traffic.

In the special, but highly relevant, case when transmitter and receiver cannot hear each other and there exist no nodes to relay via, in-network aggregation is insufficient. In conjunction with the need for mapping communication performance using larger sets of observations collected over longer periods of time, infrastructure-based aggregation and dissemination is proposed in Paper VI.

The main contributions of Paper IV are the formalization and evaluation of a method for collaborative radio quality map-building that is independent of fixed infrastructure. The proposed method is based solely on real-time observations of not only successful but also failed communication attempts at specific locations, in contrast to methods based on statistical models or location-agnostic link strength measurements.
5.5 Expressing QoS requirements

Paper V describes a quality-of-service specification format for cooperative traffic applications. The specification format allows the application designer to express requirements on both minimum CAM inter-arrival times as well as required coverage. For CAM inter-arrival time we adopt the T-Window reliability metric first proposed by Bai and Krishnan [3]. However, we also recognize the need for novel specification component relating inter-arrival time requirements to spatial applicability. In other words, to where must a specific level of communication quality be maintained? Furthermore, such a spatial requirements specification is likely to be highly dynamic and dependent on the state of the traffic environment.

The communication QoS specification is one of the components in a monitoring and adaptation framework. By registering the requirements specification with a QoS monitoring service, the application can invoke adaptation routines in response to notifications that communication requirements are unlikely to be met.

The paper explores how a QoS specification can be made context-dependent by formulating the coverage component as road segment selection rules, which yield different coverage depending on the ego vehicle location and movement. Under the assumption that a digital road map is available, the required coverage is specified as a subset of road segments from the map using two selection functions, Flood and Trajectory which respectively allow distance-based and time-based selection. Combinations of sets of road segments can also be formed using set theoretic operators and nesting of the two selection functions. To each coverage specification a T-Window reliability metric is assigned. The communication requirements for a given application are thus defined by, possibly multiple overlapping, such coverage and quality specification pairs.

5.6 Monitoring the communication environment

Paper VI combines the communications requirements specification presented in Paper V with a radio mapping approach that relies on centralized infrastructure for data aggregation.

Vehicles log both own CAM transmissions as well as CAMs received from other vehicles. To reduce the size of the reception log, of which the growth is a-priori unknown, compression using a Bloom filter is employed. Received messages are hashed and stored in the filter which is periodically uploaded to a central server for aggregation. During the aggregation stage transmission log records are used to perform look-ups in the reception log Bloom filters in order to detect failed CAM deliveries. The Bloom filter compresses the received message log by allowing a controllable level of false positives when performing look-ups.
Discrete communication observations, representing either a failed or successful CAM transmission, are associated to road segments using a digital road map as well as spatially binned. The spatial binning serves to interpolate communication measurements at discrete positions also to nearby locations. The resulting map consisting of recorded packet reception rates (PRR) for road segment pairs is re-distributed to nodes via the infrastructure.

Comparison between the communication requirement specification and the radio map is performed by first evaluating the coverage requirements over a series of time points and then extracting the mean packet reception rate for each required road segment pair at each time point. Other statistics may also be used rather than the mean, for example the minimum packet reception rate. The series of PRR values is compared to the T-Window reliability specification by verifying that the probability of receiving at least one CAM during the required time window is larger than the specified T-Window probability.

The paper concludes by identifying how the proposed mapping and monitoring approach can be used for adaptation not only in-vehicle but also on a network level. During system design, prototype application requirements can be evaluated against radio maps to indicate how well such requirements can be fulfilled in a real traffic environment. This enables feedback to the developer, allowing trade-offs to be made between application functionality and communication requirements. The approach also offers the possibility for infrastructure providers to prioritize deployment of road-side units for improving inter-vehicle communication, as well as for evaluating the effectiveness of deployed infrastructure.

The main contributions of Paper VI are thus the application of the Bloom filter hashing technique for compression of reception logs, the analysis of the feasibility of the method in terms of storage and transmission resources as well as how the resulting radio map is evaluated against the communication quality specification proposed in Paper V.
Cooperating vehicles that utilize wireless communication enables new types of services for increasing traffic safety, efficiency and comfort. Direct communication enables sharing of explicit information, distributed coordination and environment perception beyond line-of-sight.

For many of the envisioned low-latency safety critical applications, such as collision avoidance, message reception from vehicles in areas of interest is important. The types of networks that have been studied do not in general have high demands on bandwidth, vehicles exchange relatively compact messages at a modest rate. Instead focus is on demands for reliable delivery, and even more importantly demands on the predictability of delivery performance. In contrast to optimizing average case performance, knowledge of worst-case performance has been one of the themes of this thesis. If it is a-priori known that communication is poor at a specific location graceful degradation is possible of the application functionality.

A major influence on the performance of inter-vehicle communication at proposed frequencies around 5.9 GHz is the presence of non-line-of-sight conditions between transmitted and receiver. Such slow-fading characteristics are often amenable to mapping as they are caused by static features such as terrain or buildings. We have performed measurement campaigns to characterize the influence of non-line-of-sight conditions on packet reception rate for 5.9 GHz vehicle-to-vehicle communication. The measurements show that significant packet drops can be observed in urban as well as rural settings due to static obstacles causing non-line-of-sight between transmitter and receiver.

Based on the observed degradations during non-line-of-sight vehicle-to-vehicle communication we have proposed methods for mapping packet reception rate by logging message transmissions and receptions within vehicles in the network. The first method performs aggregation within the network, without the need for centralized infrastructure. In-network aggregation allows rapid mapping of a specific location, however it is difficult to collect large observation sets as storage is distributed among the nodes themselves. Through simulations
we have shown that decentralized aggregations is beneficial but that it is also vulnerable to network partitioning and sparse network conditions.

The second proposed aggregation method relies on centralized infrastructure to which transmission and reception logs are periodically uploaded. The method does not require any additional messages to be transmitted between vehicles in addition to the cooperative awareness messages already sent during normal operation. Long term mapping of the radio environment is made possible by centralized aggregation, enabling the use of radio maps also for off-line analysis such as road-side unit placement and requirements analysis.

The thesis has further explored how already existing traffic coordination rules can be modeled and used in an automated system. Inspired by how drivers already today coordinate in traffic using limited visual communication, but with a rich set of behavioral rules, we have investigated how pre-shared models can be used to achieve cooperative traffic safety services. Experimental evaluation of the ability to predict driver turning intent has been made using vehicle traces collected from a video sequence of an intersection showing that such prediction is feasible. Furthermore, we have provided an implementation of a cooperative pedestrian crossing application relying on pre-shared models of normative behavior. A novel warning criterion that analyzes the distribution over possible driver intentions has also been proposed. The warning criterion has been experimentally evaluated using reference maneuvers collected in an instrumented vehicle, correctly classifying hazardous maneuvers.

6.1 Future work

Although we have chosen to explore the extremes of in-network versus infrastructure-based aggregation a middle path between the two is certainly possible. Hybrid approaches could for example utilize in-network aggregation with infrastructure supported dissemination of radio maps.

Whereas our approach to mapping the communication environment relies solely on gathered measurements the ability to augment such empirically gathered datasets with information from radio propagation models is an interesting research direction. Such augmentation would be valuable in situations where communication measurements are likely to be sparse, for example in rural environments, or when the system penetration rate is low. Furthermore, feeding measured data back to the modeling stage could be used to improve the propagation models themselves, generalizing measured communication quality in one situation also to similar situations.

Further studies into the trade-offs between communication performance and communication predictability are also motivated by the conclusions of this thesis. Much in the same way that complex techniques for increasing computational performance, such as speculative execution, make execution time unpredictable so does highly adaptive coding and routing strategies make inter-vehicle communication performance unpredictable. Given a communication
monitoring approach as presented in this thesis, can more robust safety-critical systems be constructed by sacrificing performance for predictability?

The proposed radio mapping method is mainly suitable for detecting disturbances caused by geographically static objects, such as is the case when non-line-of-sight is caused by a building or terrain. During our work in the area of cooperative platooning it has become apparent that severe degradation in communication performance can also be caused by NLOS due to dynamic obstacles such as large trucks. A future topic of investigation is whether radio maps can be created for such scenarios as well. It is conceivable that a mapping approach similar to our in-network aggregation method can be useful for this purpose, possibly in a hybrid system that also utilizes models of radio propagation to predict how other vehicles will affect communication quality.
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