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Feasibility study: Advanced Co-operative Overtaking System using Vehicular Ad-Hoc Networks

by

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Nomenclature

AASTO American Association of State Highway and Transportation Officials

ABS Automatic Brake System

ADAS Advanced Driver Assistance System

ADSL Asynchronous Digital Subscriber Line

ALOHA –

ART Acceptance Range Threshold

ASTM American Society for Testing and Material

ASV Advanced Safety Vehicle

BST Base Station Transceiver

C2C-CC CAR 2 CAR Communication Consortium

CSBC Circuit-Switched Broadcast Channel

CDMA Code Division Multiple Access

CEPT European Conference of Postal and Telecommunications Administrations

CSAH Client-Server Ad-Hoc

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

CTS Clear To Send

DLC Data Link Control

DSRC Dedicated Short Range Communications

ER Environment Representation

ETC Electronic Toll Collection

FCC Federal Communications Commission

FI Frame Information

GPS Global Positioning System

GUI Graphical User Interface

ICI Inter Carrier Interference

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

ITS Intelligent Traffic Systems

LAN Local Area Network

LLS Lower Level Service

MAC Medium Access Control

MANET Mobile Ad-hoc Network

MBV Map-Based Veri cation

MDT Maximum Density Threshold

MHVB Multi-Hop Vehicular Broadcast

MGT Mobility Grade Threshold

NS-2 Network Simulator 2

PHY Physical (Layer)

OFDM Orthogonal Frequency-Division Multiplexing

OSI Open Systems Interconnection

QoS Quality of Service

R-ALOHA Reservation ALOHA

RTS Request To Send

RSSI Received Signal Strength Indictor

SNR Signal to Noise Ratio

TDMA Time Division Multiple Access

TTC Time To Collision

UMTS Universal Mobile Telecommunications System

UTRA TDD UMTS Terrestrial Radio Access Time Division Duplex

VANET Vehicular Ad-hoc Network

WAVE Wireless Access in Vehicular Environments

WLAN Wireless LAN

ZDP Zone Diffusion Protocol

ZFP Zone Flooding Protocol

Chapter 1

Introduction

1.1 Motivation

Globally, the need for transportation and mobility has grown exponentially. Every day millions of people around the world climb into their vehicles to drive themselves. Unfortunately, each individual is faced with a fair risk of being involved in a traffic accident. Over 40,000 traffic fatalities occur annually in both the United States of America (USA) and the European Union (EU). As a result of these deaths, improving road safety has been adopted as a major objective. The EU set a goal in 2001 to have the number of road deaths reduced to 50% by 2010 [4] [5].

New tools, such as navigation systems and traction control, aid drivers on the road. Eventually these new advances will be coupled with rising technologies in so-called *smart cars*. As a result, these *smart cars* will be implemented with a large set of Advanced Driver Assistance Systems (ADAS). The goal of such ADAS is to ease the driving experience, improve overall traffic flow, and minimise human error. It is believed that such systems can help to decrease the number of road accidents. A new approach that has recently emerged allows co-operation among vehicles by means of telecommunications. Communicating vehicles can detect, address, and thereby help to prevent hazardous traffic situations.

Such a communication platform is provided by a Vehicular Ad-hoc Networks (VANET). The nodes in these networks are typically vehicles, but the system can also comprise stationary road-side equipment. The VANET uses communication from all vehicles in the area along with any stationary equipment to establish a dynamic self-configuring network. However, due to the constantly changing nature of vehicular traffic, node topology is arbitrary and highly unstable. Owing to this, vehicle-to-vehicle communication is a challenging field of research.

This thesis researches whether it is feasible to assist a driver with the overtaking of another vehicle on a two-way road by means of a VANET dissemination protocol. For this purpose such a protocol was developed, simulated and analysed.

1.2 Justification

From all lethal traffic accidents a substantial subset can be directly related to overtaking. A plausibly explanation is that the overtaking manoeuvre is a complicated task for the driver. Especially the overtaking on rural two-way roads - with over twenty sub-tasks for the driver - is very demanding [2]. Driver assistance on several of these tasks is therefore expected to reduce the number of collisions due to overtaking. Also, a survey has indicated that amongst drivers there is a demand for such specific assistance [6].

Current ADAS developments towards overtaking have mainly focussed on the application on one-directional roads and have not yet incorporated VANET technology. On the other hand, VANET initiatives such as the CAR 2 CAR Communication Consortium (C2C-CC) and SAFESPOT have indicated the urge for more driver assistance and traffic awareness, but have not yet presented any proposals on this specific topic [7] [8].

Within the broad range of VANET research there is an increased interest for data dissemination models. Many of the proposed models focus on collision avoidance systems that require real-time traffic information from their direct vicinity. In contrast, for an overtaking assistant it is seminal to be aware of far-ahead opposing vehicles. For that reason a new approach is required for fulfilling the need to sense traffic participants over relative large distances.

Although there is a demand for overtaking assistance on bi-directional roads, none of the current dissemination protocols has yet been designed for this specific purpose. This thesis aims to provide a first step in the development on an Advanced Co-operative Overtake System (ACOS) by proposing such a protocol.

1.3 Research questions

This work's main objective is to asses whether it is possible to develop an overtaking assistant for two-way roads based on wireless communication among cars. The following questions and sub-questions are to be answered.

1. Selection of Vehicle Ad-Hoc Network.

   (a) What Vehcicle Ad-Hoc Network is most suitable for an Advanced Co-operative Overtaking System?

   (b) What are this technology's current issues?

2. Definition of service requirements for an Advanced Co-operative Overtaking System.

   (a) What distances have to be covered by means of wireless communications?

   (b) What information has to be exchanged among the vehicles?

3. Feasibility of an Advanced Co-operative Overtaking System.

   (a) Is it possible to bridge the distances that results from question 2.a?

   (b) Could such a system be applied to trigger overtaking manoeuvres?

   (c) Could such a system contribute to a safer traffic environment?

1.4 Target audience

This work aims to serve two distinct groups: those performing research on VANET technology (telecommunications engineering) and those researching driver assistance systems (civil engineering).

For the first group insight is provided on the state of the art of VANETs, the design of this particular dissemination protocol, and a performance evaluation. This work's value for the other group is how wireless networks can contribute to a safer traffic environment by the acquisition of information about surrounding vehicles. Occasionally some basic telecommunications knowledge will be explained, since this thesis covers two traditionally unrelated disciplines.

1.5 Outline of this thesis

This section briefly describes how this research is performed. As a preparatory work the *state-of-the-art* of VANET technology is given by Chapter 2. It describes the history of this field of research, several design approaches and a set of major issues this technology has to cope with. At the end of Chapter 2 a type of network is adopted to be used in this research.

The next step is a definition of the system requirements for the ACOS (Chapter 3). To reach this goal, the overtaking manoeuvre is modelled and analysed in detail. The most valuable output of this chapter is an insight in what distances have to be bridged by the ACOS for giving a recommendation on a passing manoeuvre.

This knowledge is then applied in Chapter 4 to design the necessary dissemination protocol. Its functioning and syntax is presented to the user, together with all the required system building blocks.

A simulator was developed in the JAVA programming language for measuring the influences of certain parameters on the protocol's behaviour. How the underlying VANET is simulated and what results were acquired is displayed in Chapter 5. These results are then summarised and evaluated in Chapter 6, the protocol's performance is compared against the system requirements as defined in Chapter 3.

Finally, the Epilogue (Chapter 7) answers the research questions and summarises how these problems have been tackled. Furthermore the chapter gives an overview for any future work that can be performed in a follow-up research.

1.6 Related research

This section introduces several projects that are related to the development of an ACOS. These projects are ROADAS, TrafficView, C2C-CC[1] and SAFESPOT. The author refers to Chapter 2 for an elaboration on VANET technology.

1.6.1 ROADAS

The ROADAS[2] project, conducted at the Delft University of Technology, analyzed the potential safety effects of ADAS on two-way roads. Part of this research was collecting data on passing behavior that led to the development of detailed descriptions of distinct passing manoeuvers. This data was then used to carry out a driving simulator experiment to investigate the functioning and acceptance of a passing assistant. Throughout the experiments, participants were presented a red or green signal indicating whether it was possible to overtake another vehicle.

Results showed that driving with an active overtaking assistance (a green light indicating that it was safe to pass and a red light indicating that it was dangerous) increased the frequency that drivers passed another vehicle and improved traffic flow. Furthermore, differences in passing behavior among the participants compared to a base experiment without the overtaking assistant became smaller and thus more predictable. In addition, the numbers of dangerous traffic situations were reduced and drivers who before showed inhibited behavior now displayed an increased willingness to overtake slower vehicles.

What can be concluded from the ROADAS project is that an overtaking assistant is likely to contribute to a better traffic flow and more predictable driving behavior. Field measurements and simulation results from ROADAS contributed to define the service requirements in this research [6] [9] [2] [10].

[1] CAR 2 CAR Communication Consortium

[2] Research on Overtaking and Advanced Driver Assistance Systems

1.6.2 TrafficView

The TrafficView project was an initiative by Rutger's University. Their research focussed on the development of a framework to allow the dissemination of vehicle information. One of their goals was to improve road safety by using active accident-prevention mechanisms. A prototype application was developed that, by means of a graphical user interface, presented the driver a real-time view of nearby vehicles. The following main research issues had to be tackled: data validation, data aggregation, on-demand traffic query, traffic modeling, and simulation. Although their research did not focus on the overtaking maneuver itself, they succeeded in developing a real-time 'radar' which displayed the positions of other vehicles on a three-dimentional map. Decision making in the ACOS is also based on a similar set of knowledge, indicating its relation with the TracView project [11].

1.6.3 C2C-CC

The main goal of the C2C-CC2 is to standardize interfaces and protocols for communication between cars and their environment. This non-profit organization was initiated and is supported by European vehicle manufacturers. They are expected to deliver the European VANET standard to be implemented in vehicles. Despite that most of their efforts are concerned with the lower OSI layers, they also focus on the application layer by means of several use cases. These are necessary to define what information has to be broadcasted by the vehicles.

1.6.4 SAFESPOT

SAFESPOT is a research project funded by the European Commission Information Society Technologies and aims to understand how *smart vehicles* and *smart roads* can contribute to road safety. Their research is aligned with the C2C-CC project and focuses on the development a Safety Margin Assistant (SMA). This SMA uses VANET technology to detect potentially hazardous situations and to increase a driver's traffic awareness in both space and time [8].

Chapter 2

Vehicular Ad-hoc Networks

This thesis is based on current knowledge of Vehicular Ad-hoc Networks (VANET). A basic explanation of this technology is essential to understanding the design choices made throughout Chapter 4 and 5. Moreover, VANET technology is not yet being implemented in practice and is still subject of research. Market penetration is not forthcoming as several main issues still are to be solved. Take note, most of this chapter is reused from a paper as written for the course *Selected Topics* at the University of Twente.

After the following short introduction a bottom-up approach is applied to explain this technology together with its current issues. Section 2.2, 2.3 and 2.4 discuss the bottom three layers from OSI Reference Model[1]: the physical, data, and network layer respectively. Section 2.5 gives a brief overview of simulation methods and finally in Section 2.6 a selection will be made for a VANET initiative that is most suitable for the ACOS.

2.1 Introduction

As a result of the developments in mobile and wireless technology, information and data transfers between moving devices is now feasible. In urban areas this will eventually result in dense network coverage, allowing to monitor and possibly practice control over geographic areas of interest. This technology will be especially beneficial for traffic management applications which are expected to gain advantage from the penetration of Intelligent Traffic Systems (ITS).

Co-operation among vehicles is a promising approach to improving traffic flow, highway safety, and providing enhanced mobile network services.

[1]The Open Systems Interconnection Basic Reference Model, or short the OSI Reference Model, is a layered and abstract description for communications and computer network protocol design. From top to bottom, the model distinguishes the following layers: application, presentation, session, transport, network, data link, and physical layer. Each layer represents a collection of related functions that provide services to the layer above it and receives services from the layer underneath.

Various consortia are currently researching VANET technology. The main topics of their research include frequency allocation, standards for physical and link layers, routing algorithms, and application development.

Dedicated Short Range Communication (DSRC) is either one-way or two-way wireless communication that is specifically designed for automotive purposes. This technology is mainly applied for Electronic Toll Collection (ETC). A transponder communicates with nodes along the road to reveal a vehicle's identity.

DSRC can be classified into two categories: Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). With V2V communication, vehicles autonomously set-up and maintain an ad-hoc network without any intervention of other entities. V2I communication allows stationary nodes, such as fixed access-points or even traffic-lights, to exchange data with passing vehicles. Example V2I applications are the gathering of traffic data and the before mentioned toll collection. Also, V2I communication can be applied to provide vehicles with real-time traffic information.

Due to the high dynamic nature of traffic, VANETs are fundamentally different from the Mobile Ad-hoc Networks (MANET). V2V communication is exposed to frequent topology changes, network fragmentation, and nodes arranged in a diminished operative networking range [12]. An advantage over traditional MANETs is that computing power and data storage are not limited [1]. Consequently, VANET technology requires a unique approach.

2.2 Physical layer

In networking terms, the physical layer (PHY) is the most basic layer. Its function is to transmit and receive raw bits of data. Because the DSRC is operates wireless, bits are transmitted by means of radio communications.

2.2.1 Frequency bands

First generations of DSRC - applied for ETC - provided short range communication and low data rates. Because these specifications no longer suited modern ITS requirements, and many legislative regions authorised distinct frequency bands, a demand for new standards emerged.

Throughout the USA and Canada, the 5.9 GHz band ($5855 \div 5925$ MHz) is presently allocated exclusively for DSRC usage. The Japanese government designated the 5.8 GHz band, an ETC legacy. Two Japanese standardised short-range V2I protocols (ARIB STD-T55 & STD-T75) are already in use, but lack V2V potential. Currently, their Advanced Safety Vehicle (ASV) endeavours a new and improved DSRC platform [13].

In American footsteps, the ETSI[2] investigated and allocated of the 5.9 Ghz

[2]European Telecommunications Standards Institute (ETSI)

band for usage the EU [14]. Their latest interim report states that the 5875 ÷ 5905 MHz band is best suitable for time-critical safety services, because it will not suffer from excessive interference resulting from other systems [15].

Meanwhile, European standardisation bodies also research DRSC implementation in the 63 ÷ 64 GHz band. This band - already allocated to ITS - allows much higher data rates and scopes to serve commercial services [15]. Although promising results are being achieved [16], the amount of current scientific interest for this band is negligible compared to DSRC as a whole.

Band (MHz)	USA	EU
5855 ÷ 5865	Safety	Service
5865 ÷ 5875	Service	Service
5875 ÷ 5885	Service	Safety & Traffic
5885 ÷ 5895	Control	Safety & Control
5895 ÷ 5905	Service	Safety
5905 ÷ 5915	Service	Safety & Traffic
5915 ÷ 5925	High Power	Safety & Traffic
6300 ÷ 6400	-	Commercial

Table 2.1: DRSC frequency allocation in the USA and EU.

The EU makes a clear distinction between safety-critical and traffic support communication, whereas in the USA an emergency high power band is reserved for special vehicles like ambulances. Briefly, from Table 2.2.1 can be concluded that a global harmonious system is not likely to arise. For the European market, the commercial 6.3-6.4 GHz band might even demand additional hardware to be implemented in vehicles.

2.2.2 Modulation

To transmit data, a modulation scheme is applied for altering electromagnetic waves in one of the frequency bands presented in Section 2.2.1. Two modulation schemes are being proposed for VANETs.

Orthogonal Frequency Division Multiplexing (OFDM) divides data over multiple lower-rate channels, modulated on a set of closely-spaced orthogonal sub-carriers. Consequently, the scheme is sensitive to frequency and phase errors with node movement increasing the probability for Inter Carrier Interference (ICI). Furthermore, the relative speed between nodes has an impact on the frequencies they perceive. To correct this, a training sequence is sent at the beginning of each packet. Due to the Doppler effect, this correction might become invalid towards the end of the packet, increasing the error rate [17] [18].

Although OFDM allows high data-rates, its performance can easily degrade when applied in a VANET environment. The ASTM[3] standardised a scheme based on OFDM (ASTM E2213) that will be replaced by the closely related IEEE 802.11p lower-layer standard when completed [19]. IEEE 802.11p is an amendment for the 802.11 PHY specifications.

Another proposal is based on Universal Mobile Telecommunications System (UMTS) technology and is an enhancement to the UMTS Terrestrial Radio Access Time Division Duplex (UTRA-TDD) scheme. It combines Time Division Multiple Access (TDMA) with Code Division Multiple Access (CDMA), defining a physical channel by its carrier frequency, time slot and access code [20].

UTRA-TDD has been developed to operate in a co-ordinated cellular network structure, several enhancements are therefore to be made. Because CDMA suffers the *near-far* problem, nodes adapt their transmission power regarding the distance towards the Base Station Transceiver (BST). In a VANET there is no BST and nodes could suffer a poor Signal to Noise Ratio (SNR). To resolve this, only a single node is allowed to transmit at a time [21].

Achieving time synchronisation involves a twofold procedure. First, the Global Positioning System (GPS) signal is used for a coarse synchronisation. With a time error below 1 μs, this signal is already accurate enough to be applied at once for transmissions [22]. Further synchronisation refinement can be attained by estimating and compensating the residual time and frequency offsets by analysis of the midambles in a received burst [21].

Summarising, OFDM - also applied in WLAN - allows high data-rates, but might suffer under VANET conditions. UMTS - having a lower data-rate - has already proven to be robust in mobile environments, but enhancements for ah-hoc operation have introduced new complications.

2.3 Medium Access Control

The data-link layer, operating on top of the PHY layer, is responsible for Medium Access Control (MAC). This MAC sub-layer provides nodes with a physical address and contains the protocol and control mechanisms that are required for channel access. Such mechanisms allow nodes to share a common physical medium, in this case a set of radio frequencies.

For VANETs, the number of nodes attempting to obtain channel access could range from the order of tens to hundreds, depending on vehicle density. To provide a communication platform for safety critical applications, QoS properties like medium access delay, reliability, latency and packet dissemination are fundamental. Two main approaches towards MAC for VANETs

[3] American Society for Testing and Material

are discussed: based on WLAN and based on UMTS technology. Additionally, the influence of antenna characteristics on MAC design is addressed.

2.3.1 WAVE

The IEEE working group investigated Wireless Access in Vehicular Environments (WAVE) standard. WAVE is best described as family of standards that aims at high reliability and low latency for V2V and V2I wireless communication. This set of standard provides a framework that can be used for all kinds of application in the transportation environment. WAVE is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme and operates on top of the IEEE 802.11p PHY layer. Figure 2.1 gives an overview the WAVE family of standards.

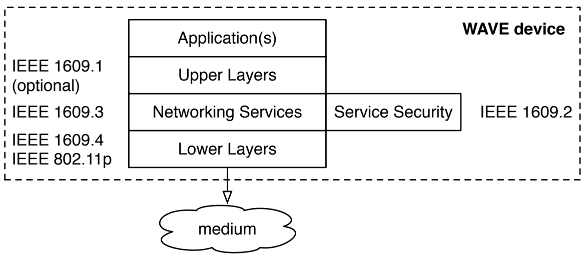

Figure 2.1: WAVE protocol stack, based on [23].

Before the PHY layer was standardised, the IEEE working groups already published higher-layer standards for trial-use; see Figure 2.1 for an overview [23][24][25].

To overcome the *hidden-node* problem, IEEE 802.11 makes use of Request To Send/Clear To Send (RTS/CTS) packets. V2V communication is exposed to rapid topology changes; once a CTS is received, the channel might already be occupied by another node moving within range. In dense areas, there is an increased probability for packet collision causing a degrading of network performance [17].

2.3.2 UTRA-TDD

A consortium of German companies and universities collaborated on the FleetNet project (2000-2003). In this project, a MAC layer was developed on top of the UTRA-TDD PHY layer. As stated in Section 2.2.2, centralized control had to be overcome. Consequently, the Data Link Control (DLC) layer was extended with the Reservation ALOHA (R-ALOHA) scheme for coordinating medium access. To reduce collision, nodes can reserve a Circuit-Switched Broadcast Channel (CSBC) for signaling purposes.

The channel is divided into repeating time frames, all divided into N time slots. Once a time-slot is reserved, it can only be used by a single node at a time. To surmount the *hidden-node* problem, it is required that each node keeps a table of all other nodes within a two-hop reach. This is achieved by sharing Frame Information (FI), containing a vector with all known nodes. As a result, the number of transmission collisions is reduced. An arriving node investigates the medium and then reserves access by inserting FI in an available time-slot.

2.3.3 MAC for directional antennas

Node movement is limited by physical boundaries and driving behaviors. The use of omnidirectional antennas gives a high probability for interference with unwanted nodes on nearby roads. Applying unidirectional antennas instead of omnidirectional antennas can, therefore reduce transmission collisions and increase channel reuse. It allows pairs of nodes located nearby to communicate simultaneously. It is shown that applying these unidirectional antennas can improve data throughput between vehicles [26].

The gain derived from using directional antennas can be cancelled out if the transmission range is increased. This is possible since directional antennas can focus all power in a single direction. Doing so leads to more interference far ahead [27].

Figure 2.2 illustrates how a combination of several directional antennas can be applied to divide the medium into sectors. Broadcasting in a selection of these sectors allows a transmitter to better target surrounding nodes. E.g. for certain purposes a performance gain could be obtained by only transmitting into the driving direction.

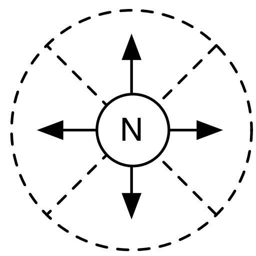

Figure 2.2: Application of 4 directional antennas.

When using directional antennas, the *hidden-node* problem is extended with *node-deafness*. Figure 2.3 illustrates a scenario where node A starts to transmit data towards node B. Collision occurs because node A is unable to overhear ongoing communication from B to C. Without MAC enhancements, the use of directional antennas increases the probability for congestion, resulting in rapid growing back-off times. *Node-deafness* can lead to packet drops, jitter and unfairness [3].

The UTRA-TDD approach is affected the least by this behavior, since all nodes within two hops are already known. Several proposals emerged to enhance CSMA/CA based MAC schemes to suit directional antennas. These include [28] where RTS/CTS packets are used to inform neighbouring nodes about the beam indices to be used. Based on this data, the other nodes can decide in what direction to beam their RTS packets. In [29] nodes are informed about communicating pairs by sending RTS/CTS packets for each transmitted data packet. While this might reduce *node-deafness*, it heavily increases control overhead. Some proposals, like [30], include use of omnidirectional broadcast solely for control packets. This type of broadcast however diminishes the advantage of spatial reuse. Another approach is to send multi-hop control messages. In [27] RTS packets are conveyed using several hops, while CTS, DATA, and ACK are limited to a single hop.

Existing models on propagation and packet loss are based on measurements conducted with omnidirectional antennas. Recently it has been revealed that antenna placement and vehicle geometry have an impact on radio behaviour [31]. In practice, omnidirectional antennas behave asymmetrically when operating at 5.9 GHz; distortion spreads up to 15 dB can be found. Best results are obtained with an antenna placed in the center of the roof of the vehicle, but this design choice is unlikely to be adopted by car manufacturers.

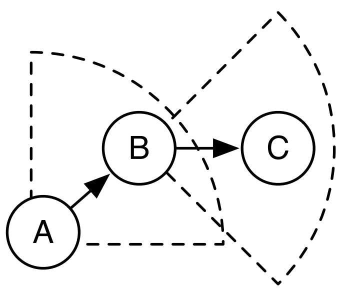

Figure 2.3: *Node deafness*, based on [3].

These results might implicate on the IEEE 802.11p standard. It suggests that for better performances the MAC design for directional antennas must be partially adopted for omnidirectional deployment. Especially QoS properties are at stake due to the incrementing back-off times [3].

2.3.4 Discussion

Table 2.2 gives an overview of the two major MAC approaches. When making a comparison, it is observed that both serve a different purpose. WAVE is better suited for mobility and does not require time synchronizations, whereas the UTRA-TDD protocol has better QoS properties, but lacks a high throughput [1]. Because safety-critical data is small in bit-size and requires a low latency, UTRA-TDD seems more appropriate for these purposes.

	WAVE	UTRA-TDD
Implementation Maturity	Mature & evolving	Moderate
Throughput (10Mhz)	< 27Mbit/s	< 1500 kbit/s
Real-time capability	Low	Moderate
QoS capability	Low	Moderate
Mobility	Medium to high	Medium
Reliable multicast	No	Yes
Time synchronisation	Unnecessary	Compulsory

Table 2.2: MAC comparison [1].

Despite the UTRA-TDD approach emerged in Europe, the C2C-CC recently decided to adopt and enhance the IEEE 802.11p standard for the European market. The C2C-CC is supported by the major European car manufacturers [7].

2.4 Network layer

Protocols for constructing and maintaining communication paths are handled by the network layer. This layer is concerned with transmission and switching procedures. Nodes are required to perform the routing themselves since a VANET lacks centralized management.

When the source and destination node of a packet are not within transmission range, a multi-hop path needs to be traversed. Otherwise, the MAC layer could have directly handled the transport. Depending on the destination(s), the source node selects one or more nodes in the vicinity and transmits the packet.

Routing protocols for MANETs can be divided in two distinct groups: proactive and reactive [32].

The proactive protocols periodically broadcast topology updates, but for VANETs this is not feasible due their dynamic nature. In contrast, reactive protocols try to discover a path before transmitting a message. Inauspicious, such a path will only last a very short time. Routing decisions therefore, must be based on locally available status information.

Several qualitative characteristics are suggested to classify MANET routing algorithms in [33], these include:

– **Loop-freedom**, a path should be inherently free of loops;

– **Distributed operation**, the amount of network knowledge available in a single node;

– **Path strategy**, ranges from single-path to flooding, a trade-off is multi-path by combining several single-paths;

– and **Memorisation**, some protocols require nodes to memorise a path for a certain period of time, e.g. for QoS purposes.

Routing protocols are either unicast or multicast for deliverance at a single destination or multiple destinations respectively. With multicast a group of destinations is identified by common characteristics such as geographic constrains, vehicle properties and/or commercial service subscription. Flooding is a simple approach to deliver a message to a group larger then a one-hop range. With this technique nodes re-broadcast received packets to multiple other nodes, resulting in a non-desired broadcasts-storm [34]. To overcome this, protocols aim to reduce the number of packet duplicates while guaranteeing data progress.

Since a VANET is very dynamic, it is convenient to address packets with a geographic destination. This is supported by location-based routing protocols. They make relay decisions based on the positions of surrounding nodes, typically GPS co-ordinates. Some applications require deliverance to all nodes within a certain perimeter of relevance. For this purpose a location-based multicast protocol is used, better referred to as geocast.

2.4.1 Data dissemination

Recently there has been increased interest for VANET routing protocols. This has resulted in a broad range of proposals. The authors have chosen to present a concise description of a limited set of these protocols. The selected approaches are based on their relevancy to safety-critical applications and to efficient packet dissemination among a restricted selection of nodes.

Zone Flooding Protocol (ZFP) - Besides several techniques used to prevent duplicates, a packet is not relayed outside a geographical area surrounding the source node. A maximum hop-count is used to prevent keeping a message alive indefinitely within the determined zone [35].

Zone Diffusion Protocol (ZDP) - This protocol segments the road into consecutive equal sized cells. Periodically a node collects information from the cell where it is located and stores this in an Environment Representation (ER) entry that is broadcasted to nodes in the vicinity. This ER is not relayed any further but instead is aggregated with the receiver's ER. Relatively little network resources are used because nodes only single-hop broadcast their ERs. This method also introduces a delay [35].

Multi-Hop Vehicular Broadcast (MHVB) - This is a basic protocol where packets are relayed based on position information from neighboring nodes. Whenever a node receives a packet, it sets a retransmission delay correlated to its distance towards the originator. The policy is such that the most remote node relays the packet with the shortest delay [36].

Client-Server Ad-Hoc (CSAH) - This method is comparable to the MHVB protocol but with a more sophisticated technique to select the forwarding delay. Besides a random seed, the numbers of nodes within a one-hop and two-hop range are required to be considered [37].

TrafficView Using this protocol, two types of messages are broadcasted by a node; (1) *generated data* containing only information about the node itself and; (2) *relayed data* with knowledge about other nodes. The road in front of a vehicle is divided into cells. Every cell is aggregated with a rate a_i that increases with the distance to the node. For example, records from two other nodes are aggregated into a single record when those nodes are positioned close to each other and travelling at relatively similar speeds. In addition, an ageing algorithm is applied to discard obsolete data [11].

Another study focused on whether dissemination is affected by applying preferred paths on two-way roads. Simulations were used and it was noted that nodes moving in opposite directions were best suited for packet forwarding [38].

ZFP and ZDP emphasize that a balance must be found between node awareness and network utilization. Data aggregation, such as in TrafficView, allows keeping the transmitted data rather compact, while the advantage of MHVB and CSAH is to delay the nodes least suitable for relaying.

Other proposals worth mentioning include the research as described in [39], where is chosen for an altruistic approach. Each node individually determines whether a packet is valuable to a neighbouring node or not. Decision making is based on message, vehicle and information context [40]. In [41] and [42] protocols are described for propagation over multi-hop paths covering larger areas.

The carry and forward technique is another approach. This method is better suited for delay tolerant applications and for use in areas where traffic is sparse. A node holds data until another vehicle enters its vicinity and then forwards it. By means of this technique, a message can be delivered over disruptive paths. Examples can be found in [43], [44] and [45].

Some advanced routing protocols might show good performances under particular conditions but execute poorly overall. In contrast, simple operating protocols can provide a reasonable overall performance and can profit from advantageous circumstances. The ideal dissemination protocol should therefore be able to adapt to varying situations such as traffic volume and speed, urban or rural settings, vehicle direction, etc.

The authors refer to [33] for a taxonomy of MANET location-based unicast protocols and to [46] for a survey on geocast protocols.

2.4.2 Node localisation

Many proposals require nodes to be location-aware. This can be achieved using simple and available GPS technology. A relatively precise estimation is performed by comparing the GPS signals received from at least four satellites. GPS has an average accuracy within 10 meters [47], but the GPS signals are not always available. This can be due to interference or when line-of-sight with these satellites is lost. Localisation solely based on GPS might therefore not be sufficiently reliable to be applied in safety-critical applications.

In [48] a method is described where every T seconds nodes measure their distance - e.g. by using a Received Signal Strength Indictor (RSSI) - towards neighbouring nodes and broadcast this data. An algorithm is then used to refine the (weakened) GPS signal with an average accuracy improvement of 3 meters. Another approach is taken in [49] where locations are assigned to nodes unable to receive a GPS signal themselves. Simulations show that this method is reliable when at least 60% of the nodes is aware of its locations, the other 40% can then be recovered.

When nodes broadcast forged position information, the performance and security of routing protocols becomes affected. To reduce this effect, a method is presented in [50] for position verification. The trustworthiness of a position is analysed by combinations of the following techniques: Acceptance Range Threshold (ART), Mobility Grade Threshold (MGT), Maximum Density Threshold (MDT) and Map-Based Verification (MBV).

2.5 Performance evaluation

This section gives first a short introduction to VANET simulation after which the reader is presented with a brief overview of several performance assessments performed on VANET protocols.

2.5.1 Simulation

In the development process of a VANET protocol, simulation is a powerful tool to gain insight in how it performs once deployed. Simulation is even quite seminal, because authentic DSRC equipment is presently unavailable.

The Network Simulator 2 (NS-2) is a widely used application and provides a IEEE 802.11 simulation architecture [51]. Because it does not support vehicle network specific topologies and traffic control models, several enhancements are proposed. In [52] a more realistic DSRC simulation is acquired by altering MAC and PHY behaviour. To incorporate the asymmetric radio behaviour, a NS-2 extension is provided in [31]. MOVE is a tool that allows to generate realistic mobility models based on real maps; it has an interface towards NS-2 for simulation scripts [53].

Another application is GrooveNet, which is initially designed to simulate VANET communication and is based on real street maps. It supports multiple network interfaces and localisation by GPS [54].

Frequently, researchers develop custom simulations to asses the performance of proposed VANET protocols. In addition, most of these assessments are performed with different assumptions and mobility models. Therefore it is difficult to make a reliable comparison between the available performance figures.

2.5.2 Evaluations

After enhancing NS-2, several simulations are performed in [52] with 500 nodes spread pseudo-uniformly over a single lane road. The node density equals 200 cars/km and all nodes broadcast 250 bytes of payload with a frequency of 10Hz. The transmission power is arbitrarily defined such that a receiver at the distance of 200m would have a 75% reception rate in an ideal environment.

For these settings, broadcast reception dropped below 50% for a distance of 200m and rapidly dropped below 30% over 300m. Likely, this is caused by the lack of received power correlation among nearby nodes. Once a node senses the channel to be idle and starts to transmit, a nearby node is receiving a packet from a remote located sender. Also in [31] the error-rate increased to 50% over a distance of 200m.

Much better results where found in [55] with measurements of packet delivery rates over 80% up to 400m in different scenarios. These evaluations were conducted with solely three network equipped cars and thus encountered very little interference. However, it does indicate that good performances can be achieved areas where node-population is scarce.

An analytical framework for TCP multi-hop communications on unidirectional roads is presented in [56]. From their results can be concluded that a high traffic density and diversity in node velocity leads to better TCP

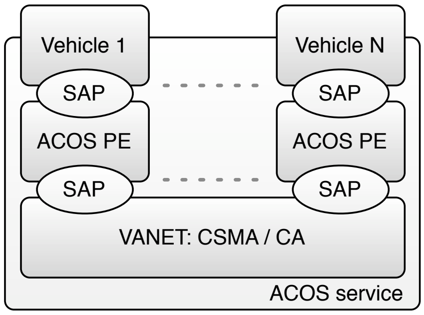

Figure 2.4: Simple protocol structure.

throughput.

2.6 Conclusions

Because the USA aims to incorporate the WAVE protocol stack and the European C2C-CC is currently developing a standard based the same IEEE guidelines, it is to be expected that upcoming VANETs will rely on the CSMA/CA MAC approach. For both continents a 10 Mhz band has already been assigned for traffic purposes, this band could be used for overtaking assistance. Therefore, as depicted in Figure 2.4, this thesis adopts the IEEE 802.11p standard as the underlying technology for the ACOS.

Partially due to the selection for IEEE 802.11p, the following main issues are to be taken into account when designing the ACOS dissemination protocol:

1. minimise the number of packet collisions;
2. overcome *node-deafness*;
3. find a good balance between node awareness and network utilisation;
4. and handling of GPS unavailability.

Please note that issues #1 and #2 are closely related considering that *node-deafness* could results in an increased number of packet collisions.

Chapter 3

Service Requirements

This chapter presents an analysis on the service requirements for the development of the ACOS dissemination model. Whereas this research is primarily concerned with protocol design, it solely focusses on communication demands. Topics such as how the ACOS eventually should be implemented in vehicles, software design and user interfaces are not within the scope of this thesis.

Requirements on the dissemination include what data is obligatory to be broadcasted, coverage range, update frequencies, packet loss and boundaries on propagation delay. To tackle this, all assets of the overtaking manoeuvre are analysed and modelled.

First, Section 3.1 portrays the presumption adopted prior to this research. Consequently node awareness, vehicle approaching and the overtaking manoeuvre itself are described in Section 3.2, 3.3 and 3.4 respectively. This chapter is concluded in Section 3.5 by giving an overview of the acquired service requirements.

3.1 Presumptions

Considering the ACOS relies on co-operation among vehicles, standardisation is an inevitable requirement for such a system to become successful. All nodes must be able to exchange the necessary messages for the system to operate. For this reason it is assumed that all vehicles are equipped with a common radio interface based on the IEEE 802.11p communication standard, as introduced in Chapter 2.

Furthermore, it is assumed that all nodes are equipped with a GPS device that is accessible by the ACOS. Nowadays a reasonable number of vehicles is already shipped with embedded GPS support. It is assumed that, by the time vehicles will be equipped with VANET technology, a GPS device belongs to every car's basic tool set.

This thesis does not assume that information about road topology or traffic regulation is available to the system. Although this might be a valid presupposition for the near future, it will make the ACOS dependent on a larger set of information, and thus more complex. Such data is therefore not taken into consideration at this stage, but could be incorporated in a followup research.

Some kind of Graphical User Interface (GUI) is assumed for information provisioning towards the driver. How and what data should be presented is not specified as this would require a full study. The only interaction taken into account is that the driver must be able to switch the front-end of the system on and off. It was found in [10] that there is a demand for such a function. Data input from the user is not considered. For certain vehicles, such as motorcycles, the implementation of a GUI might not be applicable. In these occasions the system still has to be fully operable by announcing its presence to surrounding traffic.

Like standardisation, secure VANET communication is an indispensable prerequisite for a real-world deployment. All broadcasted data has to be correct and trustworthy while vehicle privacy is assured. Establishing trust for V2V communication is a challenging issue that is not covered in this thesis. Although some methods for data validation are introduced, it is assumed that cryptography, privacy guarantees and vehicle authentication are handled by the lower OSI layers.

Summarising, the ACOS dissemination model is designed under the hypothesis of the following presumptions.

- 100 % penetration: every vehicle has a common radio interface (IEEE 802.11p).
- The system has access to real-time and accurate GPS information.
- Communication towards the driver by means of a certain GUI.
- Front-end of the system can be switched on and off.
- No data input from the driver.
- No data on infrastructures available.
- No data on traffic regulations available.
- No support by means of V2I communication.
- Security issues are handled by the lower communication layers.

3.2 Node awareness

For the ACOS it is necessary that nodes are aware of each-others' presence and behaviour. Before elaborating on the overtaking manoeuvre itself, this paragraph shows how this awareness can also be utilised for other purposes.

Research has shown that drivers have a need to be provided with information about blind spots and hidden vehicles [6]. Figure 3.1 presents an example scenario where both *Node A* and *Node B* are making a left-turn on a crossroads while *Node C* keeps driving straight forward.

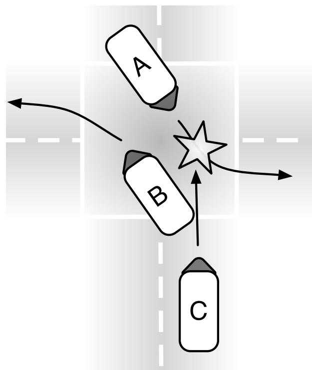

Figure 3.1: Hidden nodes on a crossroads.

Since *Node B* reduces vision for all other nodes, a hazardous situation arises when *Node A* erroneously assumes the road is clear. Many comparable situations can be thought of: vehicles leaving an exit, trucks blocking a clear vision, blind spot in the rear-mirror, etc. It is therefore important to provide a short range vision for these scenarios. Data has to be accurate and up to date because of the short physical distances and highly dynamic vehicle configurations.

As depicted in Figure 3.2, such close range knowledge is also required for the ACOS. *Node A* is slowed down by *Node B* and therefore wants to perform an overtaking manoeuvre. Due to *Node B*'s dimensions, *Node A*'s driver is unable to assess whether there is other traffic in front of the large vehicle or not. Consequently, the ACOS must be able to determine whether there is sufficient available space for *Node A* to re-enter its lane. Section 3.4 will further elaborate on this issue.

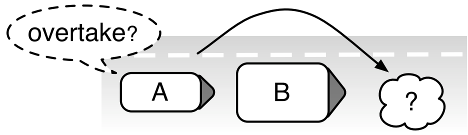

Figure 3.2: Demand for node awareness.

3.2.1 Requirements

1. Accurate knowledge about the location of all nodes within close vicinity.
2. Coverage range: small.
3. Update frequency: high.
4. Propagation delay: low.
5. Broadcast mode: periodic.
6. Data refresh-rate must be high enough to provide a reliable image.

3.3 Approaching the slower vehicle

On two-way roads the demand for overtaking is provoked by a difference in speed between two or more vehicles [9]. Dangerous situations might arise if this difference grows large. The approaching of a slower vehicle is therefore not to be overlooked since this happens prior to the overtaking manoeuvre. Examples of causes are: driving style, traffic regulations, traffic-jams, traffic-lights and vehicle breakdowns. In the U.S.A. rear-end collisions account for approximately 28% of all accidents, with driver inattention being identified as a major contributing factor [57].

The ACOS should be able to safely *guide* the driver towards the slower vehicle in front. Hence, real-time monitoring of distances between nodes in relation to their direction, velocity and acceleration is required to warn a driver for possible dangers ahead. As a result of information provisioning, the driver experiences an increased awareness and is able to safely approach the vehicle ahead.

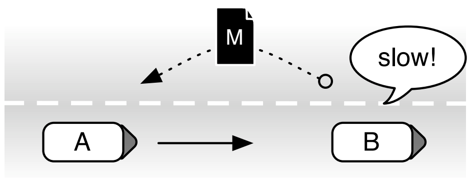

Figure 3.3: Message *M* informs *Node A* about the vehicle ahead.

This section's goal is to determine what distances have to be bridged by message *M* to warn *Node A* in time, see also Figure 3.3. This message *M* is broadcasted over the underlying VANET. Second, a method is described to give the driver an advice on the deceleration required to safely approach the vehicle in front. For doing so, the approaching manoeuvre is analysed and modelled in the following pages.

3.3.1 Approaching model

Figure 3.4 presents the approach or braking model as it is proposed in this thesis. Solely calculating with the nodes' velocities and the distance between them is not reliable. Such information would become immediately invalid when *Node B* is altering its speed. As can be seen in Figure 3.4, it is taken into account that *Node B* might be actively lowering its speed.

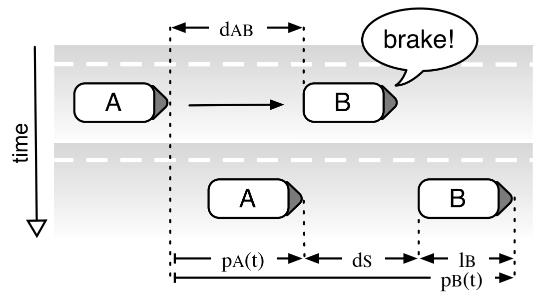

Figure 3.4: Approaching model.

The upper half of the figure illustrates the initial situation for when *Node B*'s presence is discovered. As a result, *Node A* will lower its speed conform to the data it received about the vehicle ahead. Because *Node A* has no knowledge for how long *Node B* will continue to decelerate, it always has to be assumed that the discovered vehicle will perform a full stop given a constant de-acceleration. Owing to this, the lower half of Figure 3.4 sketches the final - and hypothetical - positions where both vehicles have come to a halt. Conform to Figure 3.4, Table 3.1 describes a selection of the involved parameters. Take note that the function $p_X(t)$ gives the relative position for *Node X* with respect to *Node A*'s initial position at time $t = 0$.

3.3.2 Delaying factors

Two delaying factors have to be incorporated: communication delay Δ_C and reaction delay Δ_R. The first mentioned represents the time consumed by message M to propagate from *Node B* to *Node A*. Reaction time Δ_R is needed to let the driver observe a warning from the system and to sufficiently press the braking pedal. Both delays are summed into the total delay Δ_T.

$$\Delta_T = \Delta_C + \Delta_R. \tag{3.1}$$

Parameter	Unit	Description
d_{AB}	(m)	The initial distance between *Node A* and *Node B*.
d_S	(m)	A safety distance that should always be remained between *Node A* and *Node B*.
l_B	(m)	*Node B*'s length.
v_X^0	(m/s)	*Node X*'s initial velocity.
a_X	(m/s^2)	*Node X*'s acceleration (has a negative value for deceleration).
$v_X(t)$	(m/s)	*Node X*'s velocity at time t.
$p_X(t)$	(m)	*Node X*'s position at time t.
$g_{AB}(t)$	(m)	Distance / gap between nodes A and B at time t.
Δ_C	(s)	Propagation time of message *M*.
Δ_R	(s)	Driver's reaction time.
Δ_T	(s)	Total delay.

Table 3.1: Parameters involved with the braking manoeuvre.

	d_{AB}	d_S	$\Delta_C(ms)$	$\Delta_R(ms)$	v_A^0	a_A	v_B^0	a_B	l_B
Set 1	20	2	200	1000	23.5	-7.2	20	-3.5	5

Table 3.2: Example values.

3.3.3 Node velocities

As earlier introduced in Table 3.1, the velocities $v_A(t)$ and $v_B(t)$ of *Node A* and *Node B* respectively are defined as a function of time. In the equations below, τ_A and τ_B determine at what time the vehicles are expected to have zero velocity. Take note that $t = 0$ is that moment in time when message M was created, thus Δ_C before *Node A* has received it.

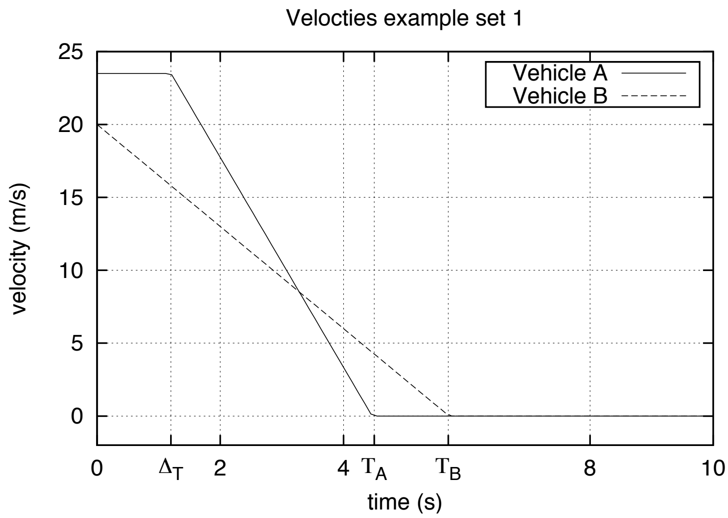

Figure 3.5: Node velocities for set 1 from Table 3.2.

Node A remains travelling at its initial speed v_A^0 until the driver starts braking after the total delay time Δ_T has elapsed. For both vehicles, the velocity decreases linearly with acceleration rates a_A and a_B until they halt.

$$\tau_A = \Delta_T + \frac{v_A^0}{|a_A|}. \tag{3.2}$$

$$v_A(t) = \begin{cases} v_A^0 & \text{if } 0 \leq t \leq \Delta_T; \\ v_A^0 + (t - \Delta_T)a_A & \text{if } \Delta_T < t \leq \tau_A; \\ 0 & \text{if } \tau_A < t. \end{cases} \tag{3.3}$$

$$\tau_B = \frac{v_B^0}{|a_B|}. \tag{3.4}$$

$$v_B(t) = \begin{cases} v_B^0 + t a_B & \text{if } 0 \leq t \leq \tau_B; \\ 0 & \text{if } \tau_B < t. \end{cases} \tag{3.5}$$

In sample set 1 from Table 3.2, two vehicles are driving with a relatively high speed and a close distance to each-other. After *Node B* starts to brake, *Node A* reacts to this with a stronger deceleration. Their speeds are plotted in Figure 3.5. Again, remind that $t = 0$ is that moment when message M was created.

3.3.4 Safety Distance

The left part of Figure 3.6 presents a critical issue not to be overlooked. With sample set 1, *Node A* first overtakes *Node B* throughout the braking manoeuvre whereas it eventually will halt behind *Node B*. It is easily concluded that *Node A*'s deceleration ($a_A = -7.2\ m/s^2$) is not advisable for making a safe stop. So, to provide the driver with a reliable advice on deceleration it is not sufficient to only determine the resulting space between the vehicles for when both have come to a halt. This could lead to very dangerous situations.

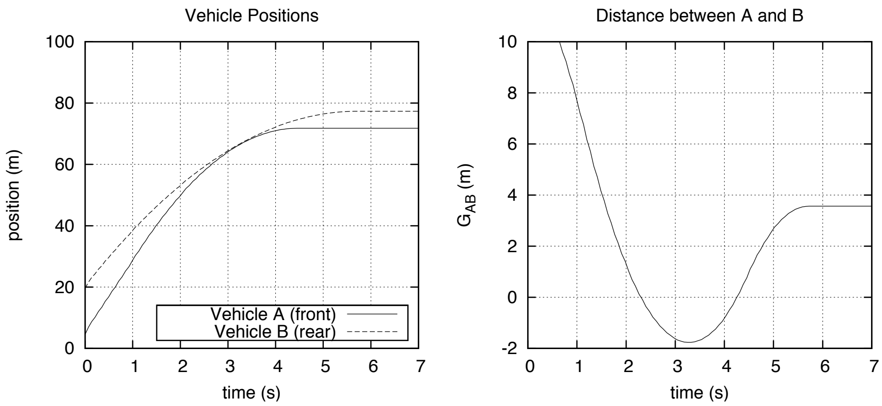

Figure 3.6: Vehicle positions and $G_{AB}(t)$.

Therefore it is required to assure a safety distance d_S that should remain between the vehicles throughout the continuance of the braking manoeuvre. To assure this, the gap $g_{AB}(t)$ between *Node A* and *Node B* as defined in (3.6) is never allowed to have a negative value. The gap is given by deducting *Node B*'s position by its length l_B, *Node A*'s position and a safety distance d_S.

$$g_{AB}(t) = p_B(t) - p_A(t) - d_S - l_B. \tag{3.6}$$

The right part of Figure 3.6 presents $g_{AB}(t)$ for sample set 1, indicating that the safety distance (d_S=2 m) is violated during the manoeuvre.

3.3.5 Node positions

Knowledge about the nodes' velocities is now used to give functions for their positions $p_{A(t)}$ and $p_B(t)$, giving the corresponding positions of the front of the vehicles at time t. The distances travelled by the nodes is acquired by taking the integral over functions $v_A(t)$ and $v_B(t)$.

Since one of the goals is to provide the driver with an advice on deceleration, position $p_{A(t)}$ is also defined as a function of *Node A*'s acceleration a_A. To simplify equations, calculations are shifted Δ_T forward in time and velocities v_A and v_B are remodelled as continues parabolae.

$$\begin{aligned}
v_A(t) &= v_A^0 + ta_A. && (3.7)\\
p_A(t, a_A) &= v_A^0\Delta_T + \int_0^t v_A(x)\,dx, && (3.8)\\
&= v_A^0\Delta_T + v_A^0 t + \frac{(a_A)^2}{2}.\\
v_B(t) &= v_B^0 + ta_B. && (3.9)\\
p_B(t) &= d_{AB} + l_B + \int_0^{t+\Delta_T} v_B(x)\,dx, && (3.10)\\
&= d_{AB} + l_B + v_B^0(t+\Delta_T) + \frac{a_B(t+\Delta_T)^2}{2}.
\end{aligned}$$

3.3.6 Minimum deceleration

The minimum deceleration required for a safe stop behind *Node B* is the lowest value for a_A where it always holds that $g_{AB}(t) \geq 0$. For doing so, g_{AB} is written as a function of t and a_A. As the node's positions were shifted Δ_T forward in time, a collision already has occurred before the driver was able to react when it holds that $p_A \geq p_B$ at $t = 0$.

$$\begin{aligned}
g_{AB}(t, a_A) &= p_B(t) - p_A(t, a_A) - d_S - l_B; && (3.11)\\
&= d_{AB} + l_B + v_B^0(t+\Delta_T) + \frac{a_B(t+\Delta_T)^2}{2}\ldots\\
&\quad \ldots - v_A^0\Delta_T - v_A^0 t - \frac{(a_A)^2}{2} - d_S - l_B.
\end{aligned}$$

For sample set 1, the plot for $g_{AB}(t, a_A)$ given in Figure 3.7 illustrates that when a_A is small enough, g_{AB} has a positive value for all points in time. As can be read from the Figure 3.8, the minimum value for a_A is approximately $-8\ m/s^2$.

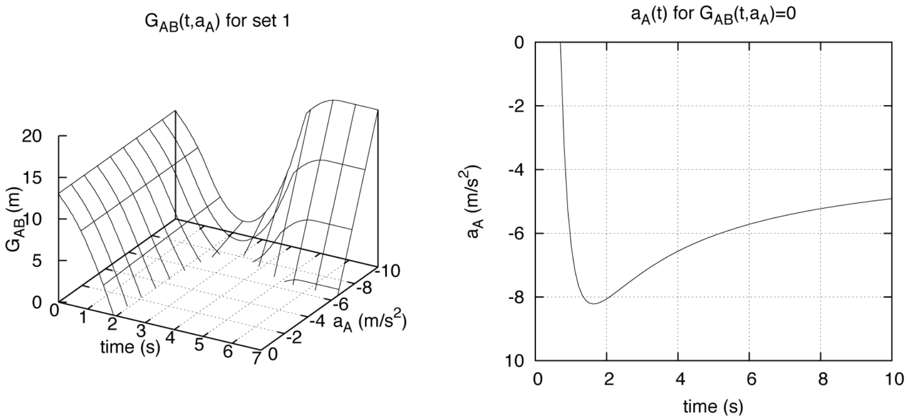

Figure 3.7: $g_{AB}(t, a_A)$ for sample set 1 and $a_A(t)$ for the $g_{AB} = 0$ plane.

To determine the value for the minimal deceleration a_A^{min} for a safe stop behind *Node B*, $g_{AB}(t, a_A)$ must be equalled to zero. Rewriting will then give the function for $a_A(t)$ in the $g_{AB} = 0$ plane.

$$\begin{aligned} a_A(t) &= \frac{2d_{AB} - 2l_B + 2v_B^0(t + \Delta_T) + a_B(t + \Delta_T)^2}{t^2} \ldots \\ &\quad \ldots \frac{-2v_A^0\Delta_T - 2v_A^0 t - (a_A)^2 - 2d_S}{t^2}, \\ &\quad for\ g_{AB}(t, a_A) = 0. \end{aligned} \tag{3.12}$$

As visualised in the right part of Figure 3.7, a_A^{min} can now be found at time t where $a_A(t)$ has the lowest value, thus where $\frac{d}{dt}a_A(t)$ equals zero. This always holds because when $\frac{d}{dt}a_A(t) = 0$ before both vehicles have stopped, the gap g_{AB} will again grow larger from this point on when a_A^{min} is applied. In the other occasion,where $\frac{d}{dt}a_A(t) = 0$ at the moment both vehicles have zero velocity, *Node A* will come to a halt with exactly distance d_S towards *Node B*.

$$\begin{aligned} \frac{d}{dt}a_A(t) &= -\frac{2(v_B^0 t + a_B\Delta_T t - v_A^0 t + 2d_{AB} - 2l_B}{t^3} \ldots \\ &\quad \ldots - \frac{2(2v_B^0\Delta_T t + a_A(\Delta_T)^2 - 2v_A^0\Delta_T - 2d_S)}{t^3}; \end{aligned} \tag{3.13}$$

$$a_A^{min} = a_A(t)\ , where\ \frac{d}{dt}a_A(t) = 0. \tag{3.14}$$

For sample set 1 from Table 3.2 the following values are found: $\frac{d}{dt}a_A(t) = 0$ on $t = 1.63$ and $a_A(1.63) = -8.22$. Figure 3.7 presents the braking manoeuvre with this new acquired value for the deceleration. It is now 'assured' that the nodes will not collide. Please note that in Figure 3.8 at $t = 2.83$ $(1.63 + \Delta_T)$[1] both vehicles are exactly safety distance d_S meters dispersed from each-other.

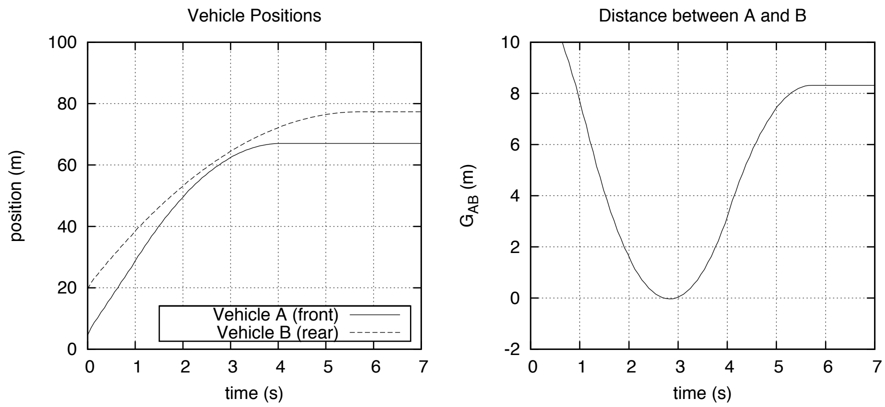

Figure 3.8: Positions $p_A(t, a_A)$, $p_B(t)$ and corresponding gap $g_{AB}(t, a_A)$.

3.3.7 Distance to be bridged by the VANET

To estimate the minimal distance d_{min} that has to be covered by means of communications to warn an approaching vehicle sufficiently in time, *Node B* is replaced by a stationary node. The approaching of a stationary *Node B* is the most stressing scenario considering it requires a longer braking distance for *Node A*. As the stationary node has no velocity or acceleration, d_{min} can be written as the distance travelled by *Node A* as a function of a_A and v_A^0.

$$\tau_A = \Delta_T + \frac{v_A^0}{|a_A|}; \tag{3.15}$$

$$\begin{aligned} d_{min}(a_A, v_A^0) &= v_A^0 \Delta_T + v_A^0 \tau_A + d_s; \qquad (3.16) \\ &= 2 v_A^0 \Delta_T + \frac{(v_A^0)^2}{|a_A|}) + d_s. \end{aligned}$$

Table 3.3 gives an overview for several deceleration values. For *Node A* to be informed in time, the minimal distance to be covered by message *M* should be based on bad road conditions, such as on wet surfaces. Therefore the author has chosen for $a_A = -5\ m/s^2$ as a suitable deceleration to calculate with.

For the driver's reaction time Δ_R a 1 second delay is taken into account, as recommended in [57]. They have researched the application of different

[1] In Section 3.3.5 all calculations were shifted Δ_T in time.

Deceleration	Description
$a_A = -3\ m/s^2$	Convenient stop.
$a_A = -5\ m/s^2$	Minimum deceleration as required by law and maximum achieved deceleration on wet surfaces.
$a_A = -7\ m/s^2$	The mean maximum deceleration for modern vehicles.
$a_A = -9\ m/s^2$	Maximum deceleration for vehicles equipped with the Automatic Braking system (ABS).

Table 3.3: Values for deceleration.

warning systems prompting a driver to start braking. To plot Figure 3.9, the communication delay Δ_C was arbitrary set to 200 ms. It is within the scope of this thesis to minimise Δ_C; a long delay will contribute to a larger distance to be covered by the system.

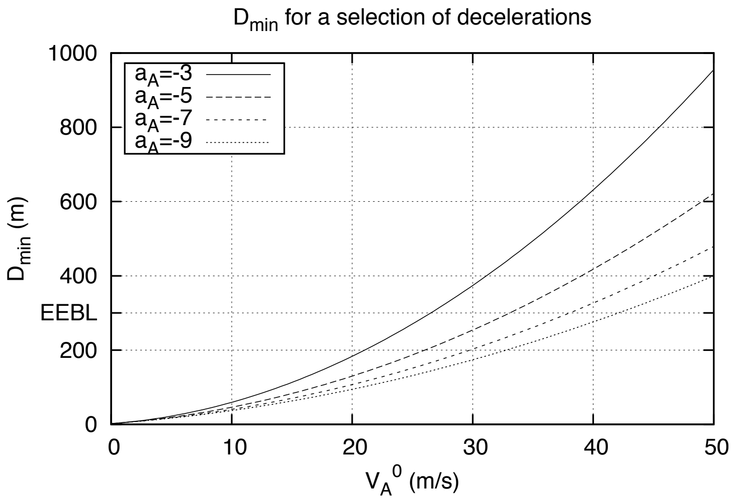

Figure 3.9: Distance d_{min} to be covered by wireless communication.

When a deceleration of $a_A = -5\ m/s^2$ and speeds up to 40 m/s are considered - not unusual on European expressways - the minimal distance to be covered by the VANET ranges to 428 m, the safety distance excluded. This exceeds over 100 m the requirements for an Emergency Electronic Brake Lights (EEBL) system as it is proposed by the U.S. Department of Transportation [19].

3.3.8 Discussion

Below some significant issues are discussed that have not yet been addressed.

No fluent braking

From the research in [57] can be concluded that drivers usually don't brake fluently, but tent to vary their deceleration throughout the manoeuvre. This addresses a problem for parameter a_B broadcasted in message *M*. If *Node B* is decelerating fast and just lifts the pedal for a fraction of time during the creation of message *M*, this might result in unwanted information processed by *Node A*. Consequently, it is be better to compose a_B from several samples, instead of performing a single measurement.

Position accuracy

Positions p_A and p_B are modelled as the fronts of vehicles *Node A* and *Node B*. To calculate these positions more accurate, knowledge about a car's dimensions is required. In addition, GPS devices are likely not implemented on identical locations within the cars, introducing an extra uncertainty. Somehow these errors need to be corrected. A possible solution is increasing the safety distance d_S according to fluctuations in these parameters. This method can also be applied to compensate GPS position errors.

3.3.9 Requirements

- Required knowledge about *Node B*: position, direction, velocity deceleration and a time stamp.
- Message *M* latency: as low as possible.
- Minimal communication range: up to $\sim 450\ m$.
- Broadcast mode: can be both event-driven or periodic.
- Communication type: unidirectional V2V.
- Throughout the whole manoeuvre a safety distance d_S has to be remained towards the node in front.

The above listed requirements state that knowledge about *Node B*'s direction has to be known. Such knowledge is necessary to determine whether the discovered node is heading towards the receiver or not.

For an increased accuracy, knowledge about a vehicle's perimeter should also be available. This would allow the system to better determine the vehicle's position. Furthermore, throughout the braking manoeuvre *Node B* has to keep sending new messages to allow *Node A* to anticipate on behaviour changes.

3.4 Overtaking manoeuvre

The goal of this section is to determine the distance that has to be covered by means of communication to provide drivers with an advice on overtaking. To reach this goal, a model is adopted and enhanced to describe the overtaking manoeuvre.

Figure 3.10 presents a scenario where *Node A* gets stuck behind *Node B* and therefore desires to overtake. In addition, *Node A*'s view is blocked by the large vehicle in front. When *Node A* attempts to overtake, a dangerous situation might occur when distance *D* towards *Node C* is not sufficient to complete the whole manoeuvre. Message *M* - broadcasted by *Node C* - contains information about the location, direction and velocity of its sender. This information has to reach *Node A* in time by bridging that distance *D* to reveal its presence sufficiently in advance to determine whether it is safe to pass *Node B* or not.

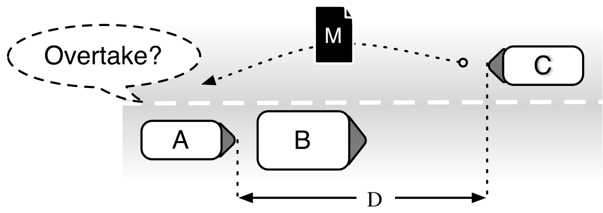

Figure 3.10: Overtaking scenario.

For acquiring the minimal distance d_{min} that has to be covered by the transmission of message *M*, the model from Figure 3.10 is further refined. Hegeman et al. have - amongst others - listed the following characteristics to describe the overtaking manoeuvre on bi-directional roads [10].

- The duration of the total overtaking manoeuvre.
- How this duration correlates with with *Node B*'s behaviour and how the manoeuvre is performed.
- The distances between *Node A* and *Node B* prior to and after the manoeuvre is completed.
- The time left before *Node A* encounters the first oncoming vehicle.

3.4.1 Overtaking strategies

The research performed by Hegeman et al. studied and identified variation in overtaking behaviour on bi-directional roads [9]. In their research the following four main overtaking strategies are distinguished.

Accelerative – *Node A* follows *Node B* and awaits a sufficient gap d_{AC} to perform the overtaking manoeuvre. For the action to be successful, *Node A* has to accelerate to higher velocity.

Flying – *Node A* approaches and immediately takes over *Node B*. Throughout the whole manoeuvre *Node A* maintains a constant speed.

Piggy backing – an extra vehicle *Node X* positioned between node *Node A* and *Node B* is introduced. Once *Node X* starts to overtake *Node B*, *Node A* immediately follows *Node X*.

Two plus (2+) – *Node A* performs an accelerative manoeuvre and takes over two or more vehicles in a single action.

From this point on will only be focussed on the *accelerative* approach. The other overtaking strategies are not taken into consideration in this research. Both the *piggy backing* and the *two plus* strategies can be modelled based on the *accelerative* approach. The only required enhancement is that the passing vehicle *Node A* has to spend more time on the opposite lane. This can be modelled by increasing the length of the impeding vehicle *Node B*.

These strategies are however more complicated to implement from the user's point of view. They (likely) require interaction with the driver to determine the desired overtaking approach. This also holds for the *flying* manoeuvre. The latter is even orthogonal to the previous described service that advises to reduce one's speed in case of slower traffic ahead. In addition, it is questionable whether the *flying*, *piggy backing* and *two plus* strategy should be supported and thus encouraged from a legislative point of view.

3.4.2 Manoeuvre duration

For *Node A*, the duration of the entire *accelerative* overtaking manoeuvre consumes T_{acc} seconds. To give an impression, Table 3.4 presents values for T as found in the previous mentioned field measurements performed by Hegeman et al. [2].

Manoeuvre	$E[T]$	σ
Accelerative	7.9	1.5
Fying	6.8	1.4
Piggy backing	7.8	2.0
2+	9.1	3.4
Total	7.8	1.9

Table 3.4: Field measurements for T [2].

These measurement cannot directly be applied to this research, since they do not incorporate variable car lengths for *Node A* and *Node B*. All values are based on the overtaking of a regular passenger vehicle, whereas e.g. the passing of a lorry would increase the required time to be spend on the opposite lane. Consequently, this implies on the total overtaking duration. Also, these measurements are performed on a single road and do not represent a variable environment.

A mathematical model by Wang et al. is adopted to describe the overtaking manoeuvre in detail. Their model allows to determine the required passing sight distance based on a set of 11 distinct parameters. The model was successfully validated against the passing sight distances as suggested by the AASTO [58].

3.4.3 Overtaking stages

The overtaking manoeuvre consists of the three stages as depicted in Figures 3.12, 3.13 and 3.14. Figure 3.11 presents the initial situation preceding Stage 1. *Node A*, *node B*, *node C* are the passing, impeding and opposing vehicle respectively.

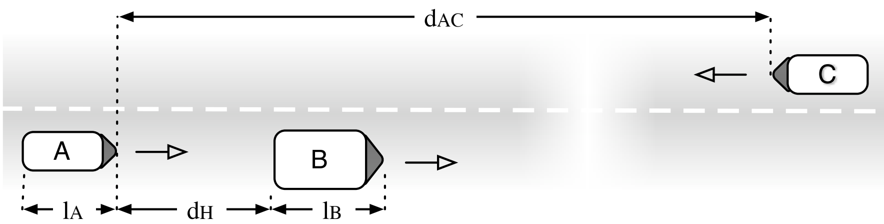

Figure 3.11: Overtaking manoeuvre, initial situation.

Stage 1 starts at the beginning of the overtaking manoeuvre and ends when *Node A* completely moved to the other lane and its front is aligned with the tail of *Node B*. The path travelled by *Node A* is described in Section 3.4.4.

Stage 2 starts at the end of phase 1 and covers that section of the manoeuvre where *Node A* is passing *Node B*, obviously while driving on the other lane in a straight line. At the end of this stage *Node A*'s front aligned *Node B*'s rear.

Stage 3 starts at the end of Stage 2 and continues until *Node A* has completed the overtaking manoeuvre by returning to its assigned lane. Just as in Stage 1, the path travelled by *Node A* is described in Section 3.4.4.

Symbols S_1, S_2, S_3 denote the distances travelled - in a forward moving direction - by the passing vehicle *Node A* during the phases 1, 2 and 3

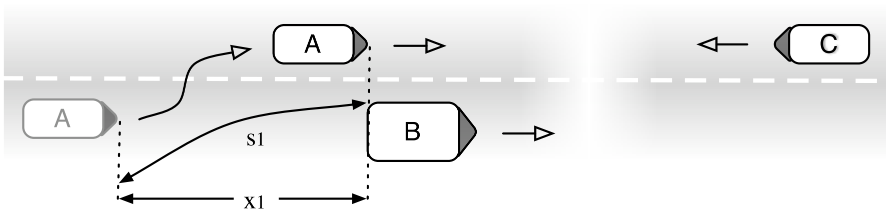

Figure 3.12: Overtaking manoeuvre, Stage 1.

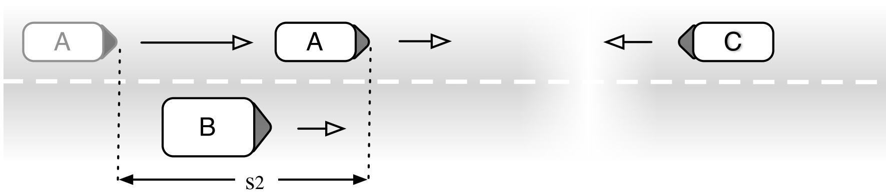

Figure 3.13: Overtaking manoeuvre, Stage 2.

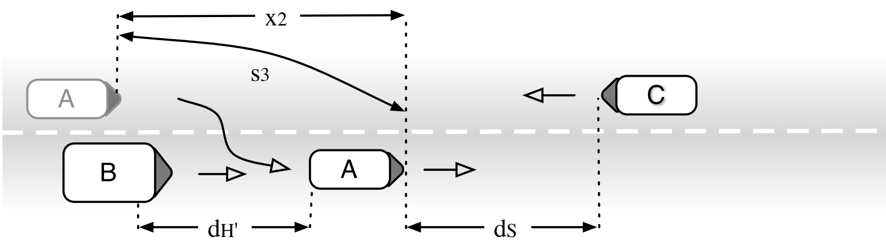

Figure 3.14: Overtaking manoeuvre, Stage 3.

respectively . X_1, X_2, X_3 are the distances travelled by the impeding vehicle *Node B* and T_1, T_2, T_3 denote the times consumed by all phases. E.g. it takes *Node A* time T_1 to complete travelling distance S_1, meanwhile *Node B* has travelled distance X_1.

3.4.4 Lane changing

In both Stages 1 and 3 *Node A* has to change lanes in order to overtake *Node B* and return to its designated lane. An example transition for Stage 1 is plotted in Figure 3.15 as function of a quintic polynomial. It presents a top view on the vehicle's position on the road, with the x-axis being the driving direction. In Figure 3.15 the vehicle moves 3.5 m sideways while travelling over a distance of 50 m. A similar graph can be obtained for Stage 3 by horizontally flipping the graph.

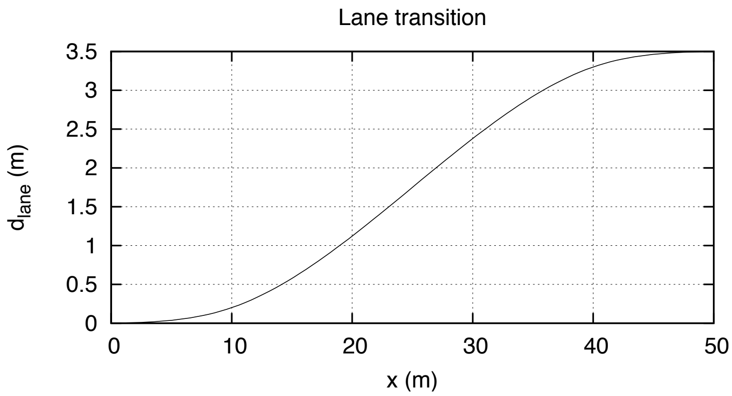

Figure 3.15: Transition between lanes.

From Figure 3.15 can easily be concluded that the length of the path travelled by *Node A* is not equal to its distance travelled on the x-axis. The length of this path has to be determined because it implies on the total duration of the overtaking manoeuvre. An approximation for the path length is given by (3.17), see [58] for its derivation. Parameter d_{lane} denotes the distance moved side-wards by *Node A*.

$$S_i = \frac{7X_i}{15} + \left(\left(\frac{8X_i}{15}\right)^2 + (d_{lane})^2\right)^{\frac{1}{2}} \quad \text{with } i = 1 \vee i = 3 \tag{3.17}$$

E.g. $X_1 = 30$ m and $d_{lane} = 4.0$ m results in $S_1 = 30.49$ m actually travelled by *Node A*. The relation between S_i and X_i given by (3.17) is later used to derive the times T_1 and T_3 consumed in Stage 1 and 3 respectively.

3.4.5 Time-space relationship

This section presents the time-space relationship for passing an impeding vehicle throughout the complete overtaking manoeuvre, as presented in [58]. The model by Wang et al. assumes that the impeding vehicle *Node B* and the opposing vehicle *Node C* travel with constant speeds, v_B and v_C respectively. Furthermore, the passing vehicle *Node A* accelerates with a_A^{max} from its initial speed v_A^{init} until its (desired) maximum speed v_A^{max} is reached. *Node A* will then continue to travel with a constant speed v_A^{max}.

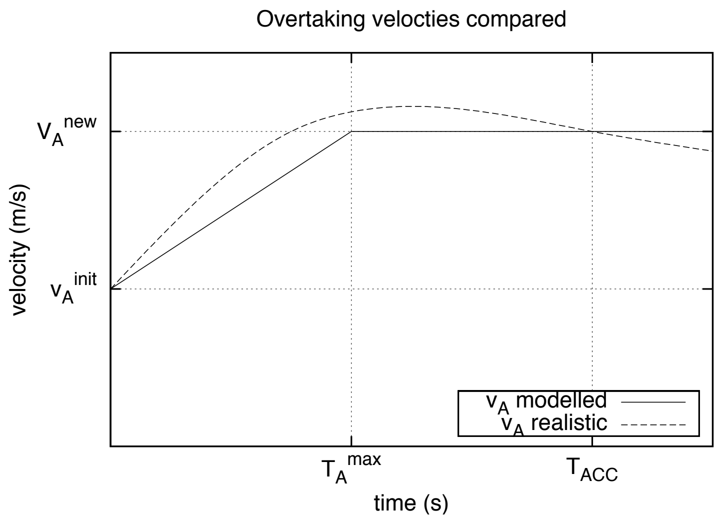

Figure 3.16: *Node A*'s velocity for sample set 1.

As depicted in Figure 3.16, the actual overtaking speed differs from the behaviour as modelled by Wang et al. The realistic pattern is not based on research, but is used to depict that changing speed is not a discrete action. Despite this inaccuracy the model by Wang et al. gives a good estimation to work with. Especially when taking into consideration that several input parameters are unknown prior to the overtaking manoeuvre itself. These latter uncertainties are of greater significance.

Acceleration

S_A^{max} denotes the required distance to be travelled by *Node A* to reach its maximum speed v_A^{max} with T_A^{max} being the corresponding consumed time. S_A^{max} and T_A^{max} are given by (3.18) and (3.19) respectively.

$$S_A^{max} = \frac{V_A^{max^2} - V_A^{init}}{2a_A^{max}}. \qquad (3.18)$$

$$T_A^{max} = \frac{V_A^{max^2} - V_A^{init}}{a_A^{max}}. \tag{3.19}$$

Depending on initial parameters, *Node A* may reach v_A^{max} in one of the three previous described overtaking stages. Another possibility is that v_A^{max} is not yet reached by the end of Stage 3. This implies that 4 different cases are to be distinguished.

Case 1: maximum speed reached at Stage 1

When S_A^{max} is reached within Stage 1, the distance travelled by *Node A* is given by (3.20). X_1 denotes the distance travelled by *Node B* and is given by (3.21). The so-called headway d_H is the clearance between *Node A* and *Node B* prior to the overtaking manoeuvre; see also Figure 3.11.

$$S_1 = S_A^{max} + v_A^{max}(T_1 - T_A^{max}). \tag{3.20}$$

$$X_1 = v_B T_1 + d_H. \tag{3.21}$$

For Stage 1 the relation between (3.20) and (3.21) is given by (3.17), the approximation for the quintic polynomial. Consequently S_1,X_1 and T_1 can be determined by simultaneously solving (3.20) (3.21) and (3.17).

In Stage 2, because *Node A* has already reached v_A^{max}, both *Node A* and *Node B* travel with the constant speeds v_A^{max} and v_B respectively. This results in the following equations.

$$S_2 = v_A^{max} T_2. \tag{3.22}$$

$$X_2 = v_B T_2. \tag{3.23}$$

To successfully perform the overtaking manoeuvre *Node A* has to gain a distance in respect to *Node B*. As visualised in Figure 3.13, this relation is described by (3.24) with l_A and l_B being the lengths of both vehicles[2].

$$S_2 = X_2 + l_A + l_B. \tag{3.24}$$

Thanks to this relation S_2, X_2 and T_2 can be determined by simultaneously solving (3.22) (3.23) and (3.24).

The distances travelled in Stage 3 are given by (3.25) and (3.26), with $d_{H'}$ being the headway towards *Node B* after the manoeuvre is completed.

$$S_3 = v_A^{max} T_3. \tag{3.25}$$

$$X_3 = v_B T_3 + d_{H'}. \tag{3.26}$$

[2] In [58] this relation was alternatively described as $S_2 = X_2$, with $X_2 = v_B T_2 + l_A + l_B$.

Similar to Stage 1, (3.25) and (3.26) satisfy the relationship as described in (3.17). Hence, S_3, X_3 and T_3 can be determined by simultaneously solving (3.25) (3.26) and (3.17).

For the other 3 cases the requisite equations are given below. A detailed description is not given since the same procedure as described for Case 1 has to be applied. The couples S_1/X_1 and S_3/X_3 are always related by (3.17), while S_2 and X_2 can be solved by applying (3.24).

Case 2: maximum speed reached at stage 2

$$\begin{aligned}
S_1 &= v_A^{init} T_1 + 0.5 a_A^{max} T_1^2. && (3.27)\\
X_1 &= v_B T_1 + d_H. && (3.28)\\
S_2 &= S_A^{max} + v_A^{max}(T_1 + T_2 - T_A^{max}) - S_1. && (3.29)\\
X_2 &= v_B T_2. && (3.30)\\
S_3 &= v_A^{max} T_3. && (3.31)\\
X_3 &= v_B T_3 + d_{H'}. && (3.32)
\end{aligned}$$

Case 3: maximum speed reached at stage 3

$$\begin{aligned}
S_1 &= v_A^{init} T_1 + 0.5 a_A^{max} T_1^2. && (3.33)\\
X_1 &= v_B T_1 + d_H. && (3.34)\\
S_2 &= v_A^{init}(T_1 + T_2) 0.5 a_A^{max} (T_1 + T_2)^2 - S_1. && (3.35)\\
X_2 &= v_B T_2. && (3.36)\\
S_3 &= S_A^{max} + v_A^{max}(T_1 + T_2 + T_3 - T_A^{max}) - S_1 - S_2. && (3.37)\\
X_3 &= v_B T_3 + d_{H'}. && (3.38)
\end{aligned}$$

Case 4: maximum speed not reached

$$\begin{aligned}
S_1 &= v_A^{init} T_1 + 0.5 a_A^{max} T_1^2. && (3.39)\\
X_1 &= v_B T_1 + d_H. && (3.40)\\
S_2 &= v_A^{init}(T_1 + T_2) 0.5 a_A^{max} (T_1 + T_2)^2 - S_1. && (3.41)\\
X_2 &= v_B T_2. && (3.42)\\
S_3 &= v_A^{init}((T_1 + T_2) + T_3) + \ldots && (3.43)\\
&\quad \ldots 0.5 a_A^{max} (T_1 + T_2 + t_3)^2 - S_1 - S_2. &&\\
X_3 &= v_B T_3 + d_{H'}. && (3.44)
\end{aligned}$$

Passing sight distance

When the right case is selected and all linear systems are solved, the so-called passing sight distance d_{AC} can be now determined by applying (3.45).

$$d_{AC} = X_1 + X_2 + X_3 + d_S + v_C(T_1 + T_2 + T_3) + l_A + l_B. \quad (3.45)$$

3.4.6 Model enhancements

The model proposed by Wang et al. allows to describe the overtaking manoeuvre based on 11 input parameters of which several are eliminated in this section. Furthermore the model is enhanced to be applicable for this research.

Node A's velocity

With the *accelerative* approach *Node A* positions itself behind *Node B* prior to the overtaking. This means *Node A* has to adapt its speed according to the impeding vehicle in front. As a result *Node A*'s initial speed equals *Node B*'s velocity. S_A^{init} becomes redundant when applying (3.46).

$$S_A^{init} = v_B. \quad (3.46)$$

Up to this point the knowledge of the desired speed v_A^{max} is taken into consideration. Inconveniently, this parameter remains unknown without the manoeuvre actually being performed. Without knowledge about v_A^{max}, it is impossible for an overtaking system to determine distance d_{AC} in advance. Another issue is that the total overtaking time grows large when the difference in speed between v_B and v_A^{max} becomes very small. In (3.47) is shown that d_{AC} grows to infinity when v_A^{max} approaches v_B.

$$\lim_{v_A^{max} \to v_B} d_{AC} = \infty \quad (3.47)$$

According to AASTO[3] v_A^{max} usually exceeds *Node B*'s velocity with $16 - 24\ km/h$, corresponding to $4.4 - 6.7\ m/s$. Another option is to assume that *Node A* will accelerate to *Node C*'s velocity. This assumption is based on the ideal event where *Node C* travels with the legislated or modal speed for that road. A major drawback for this approach is that *Node C* might not always be available. Therefore is chosen to set the additional overtaking velocity v_A^{ov} to the average expected value of 20 km/h as also used in [59].

$$v_A^{max} = v_B + v_A^{ov}. \quad (3.48)$$

[3] American Association of State Highway and Transportation Officials.

Another uncertainty is *Node A*'s acceleration a_A^{max}, since it remains unknown prior to the overtaking manoeuvre. AASTO suggests a value in the range of $0.625 - 0.669\ m/s^2$, while Sparks et al. suggest a value ranging in $3.40 - 5.11\ ms/s^2$ with an expected value of $4.0\ ms/s^2$ [59]. According to [58] the values suggested by AASTO can be considered conservative. For this reason is chosen to work with the expected value by Sparks et al. Tabel 3.4.6 gives an overview of the assumed values for several parameters.

v_A^{ov}	a_A^{max}	T_S	$T_{S'}$
$5.6\ m/s$	$4.0\ ms/s^2$	$1\ s$	$1.5\ s$

Table 3.5: Assumed values.

Headways

As explained earlier, the headway is the clearance between *Node A* and *Node B* prior to the manoeuvre. Field measurements in [9] show that this headway has an expected value $E = 17.8\ m$ with a standard deviation of $\sigma = 9.8\ m$ for the accelerative overtaking manoeuvre on $100\ km/h$[4] roads. This is a significant smaller distance compared to the generally recommended safe time distance of 2 seconds, whereas this would require a headway of approximately $60\ m$.

To reduce the time spent on the opposite lane and considering the driver to be more alert, one second is suggested to be a safe headway prior to overtaking [2]. Subsequently, the headway d_H is given by the distance travelled by *Node A* over the period T_s of one second. When taking (3.46) in consideration, d_H is given by (3.49).

$$d_H = T_s v_B. \tag{3.49}$$

When *Node A* has re-entered its lane following to the overtaking procedure, it again has to leave a headway $d_{H'}$ towards the overtaken vehicle. Now that *Node A* will move away from *Node B* due to its higher velocity, a $1.5\ s$ safe time distance is taken into account for re-entering.

In [2] is found that - manoeuvre independently - *Node A* is expected to leave a headway of $32.5\ m$ with $\sigma = 12.2\ m$. Taken the legislated speed of $28\ m/s$ into account, this corresponds to an expected $1.2\ s$ safe time distance. This indicates that the chosen value of $1.5\ s$ for $T_{s'}$ is expected to be within safety margins.

$$d_{H'} = T_{s'} v_B. \tag{3.50}$$

[4] $100\ km/h \approx 27.8\ m/s$.

Safety distance

The model proposed by Wang et al. assumes the safety distance d_S to have a fixed value. More accurate is to express d_S as a function of the Time To Collision (TCC). The TCC indicates the number of seconds it takes for *Node A* and *Node C* to pass each-other after the overtaking manoeuvre has been completed. According to [2], a safe value for the TTC is 3 seconds.

For the sake of simplicity it is assumed that *Node A* has always reached its maximum speed before the overtaking manoeuvre is completed. For Case 4, (3.51) returns a larger safety distance then actually required. Hence, this assumption has no negative implication on the driver's safety. Consequently, d_S is given by the sum of the distances travelled by *Node A* and *Node C* with velocities v_A^{max} and v_C respectively over this period of 3 seconds.

$$d_S = TTC(v_A^{max} + v_C). \tag{3.51}$$

Delaying factors

Similar to the braking scenario, two delaying factors have to be taken into account. It takes Δ_C milliseconds, the communication delay, for message *M* to actually reach *Node A*. Upon receival of message *M*, all involved vehicles have moved to other positions.

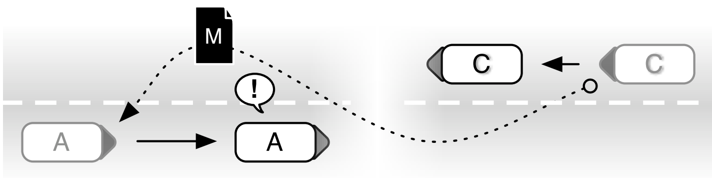

Figure 3.17: Communication and reaction delay.

When *Node A*'s driver is signalled that distance d_{AC} is sufficient large enough to perform an overtaking manoeuvre, it takes another Δ_R ms reaction time before the driver actually undertakes any action. Reaction delay Δ_R and communication delay Δ_C are summed into a total delay Δ_T. During this period Δ_T all cars convey Δ_T times their initial velocity, resulting in a delay distance d_D given by (3.53).

$$\Delta_T = \Delta_R + \Delta_C. \tag{3.52}$$

$$\begin{aligned} d_D &= \Delta_T(v_A^{init} + v_C), \quad (3.53) \\ &= \Delta_T(v_B + v_C). \end{aligned}$$

Improved model

The equations as proposed by Wang et al. can now be altered to the needs of this research. Since all 4 cases share common equations, only the unique ones are worked out and identified. The relations R1 and R2 are not modified but repeated to provide a clear overview.

$$\begin{array}{lrll}
\text{A1:} & S_1 = & S_A^{max} + (v_B + v_A^{ov})(T_1 - T_A^{max}). & (3.54)\\
\text{B1:} & X_1 = & v_B T_1 + v_B T_s. & (3.55)\\
\text{C1:} & S_2 = & T_2(v_B + v_A^{ov}). & (3.56)\\
\text{D1:} & X_2 = & v_B T_2. & (3.57)\\
\text{E1:} & S_3 = & T_3(v_B + v_A^{ov}). & (3.58)\\
\text{F1:} & X_3 = & v_B T_3 + v_B T_{s'}. & (3.59)\\
\text{A2:} & S_1 = & v_B T_1 + 0.5 a_A^{max} T_1^2. & (3.60)\\
\text{C2:} & S_2 = & S_A^{max} + (v_B + v_A^{ov})(T_1 + T_2 - T_A^{max}) - S_1. & (3.61)\\
\text{C3:} & S_2 = & v_B(T_1 + T_2) 0.5 a_A^{max}(T_1 + T_2)^2 - S_1. & (3.62)\\
\text{E3:} & S_3 = & S_A^{max} + (v_B + v_A^{ov})(T_1 + T_2 + T_3 - T_A^{max}) \ldots & (3.63)\\
 & & \ldots - S_1 - S_2. & \\
\text{E4:} & S_3 = & v_B(T_1 + T_2 + T_3) - S_1 - S_2 \ldots & (3.64)\\
 & & \ldots + 0.5 a_A^{max}(T_1 + T_2 + t_3)^2. & \\
\text{R1:} & S_i = & \dfrac{7X_i}{15} + \left(\left(\dfrac{8X_i}{15}\right)^2 + (d_{lane})^2\right)^{\frac{1}{2}} & (3.65)\\
 & & \text{with } i = 1 \vee i = 3 & \\
\text{R2:} & S_2 = & X_2 + l_A + l_B. & (3.66)
\end{array}$$

The minimal distance d_{min} to be bridged by message M can now be determined by enhancing (3.45). In (3.67) the passing sight distance d_{AC} is changed by applying the improved safety distance and adding the delaying factors due to message M's propagation delay and a human reaction time.

$$\begin{aligned}
d_{min} &= \sum_{i=1}^{3} [X_i + v_C T_i] + TTC(v_A^{max} + v_C) + l_A + l_B \ldots \qquad (3.67)\\
&\quad \ldots + (\Delta_C + \Delta_R)(v_B + v_C)
\end{aligned}$$

Table 3.6 presents an overview for when the new equations are to be applied. In Stage 1 and 2 the equations have to be solved by applying relation R1, for Stage 2 this is always relation R2.

When observing Table 3.6 one can perceive several clusters that contain matching equations. This knowledge is applied to design an efficient method

	Stage 1 (R1)	Stage 2 (R2)	Stage 3 (R1)
Case 1	A1/B1	C1/D1	E1/F1
Case 2	A2/B1	C2/D1	E1/F1
Case 3	A2/B1	C3/D1	E3/F1
Case 4	A2/B1	C3/D1	E4/F1

Table 3.6: Relation between cases, stages and equations.

to determine the minimal distance d_{min} to be bridged by message M. Figure 3.18 presents the new approach in a flow diagram. The coloured areas define to what case(s) the solve operations belong. In the worst scenario, namely Case 4, a total of 6 systems of equations are to be solved. Experiments performed by the author show out that Case 2 has the most common occurrence; the model could therefore be improved by always first attempting this particular case.

3.4.7 Distance to be bridged by the VANET

The system as presented in Figure 3.18 has been implemented in Maple to visualise the influences of several parameters on distance d_{min}. For the base scenario parameters are set to the values according to Table 3.7.

v_B	d_{lane}	l_A	l_B	v_A^{ov}	a_A^{max}	T_S	$T_{S'}$
$23\ m/s$	$3.5\ m$	$4.5\ m$	$4.5\ m$	$5.6\ m/s$	$4.0\ ms/s^2$	$1\ s$	$1.5\ s$

Table 3.7: Base scenario.

For plotting Figures 3.19 through 3.24, a single parameter is altered for each graph to show its influence on distance d_{min} to be bridged by the VANET. From Figure 3.20 can be concluded that the overtaking of a longer vehicle, such as a truck, substantially increases d_{min}. A comparable linear trend is observed in Figures 3.19 and 3.22 as a result of increasing *Node B*'s and *Node C*'s velocity respectively.

The graph given by Figure 3.21 shows that changing the width of traffic lanes - by altering d_{lane} - has a marginally influence on d_{min}. Therefore relation *R1* from (3.65) might be simplified to just $S_i = X_i$ to speed up the calculations for determining d_{min}.

Figure 3.23 shows 3 curves for d_{min} as a function *Node A*'s acceleration. Every curve represents another value for v_A^{max}. When a_A^{max} reaches 3 m/s^2 all curves bent towards an asymptote. This indicates that the driver ideally should keep up a minimal acceleration of 3 m/s^2 for a better prediction of d_{min} by the ACOS.

Another effect pointed out in both Figure 3.23 and Figure 3.24 is the

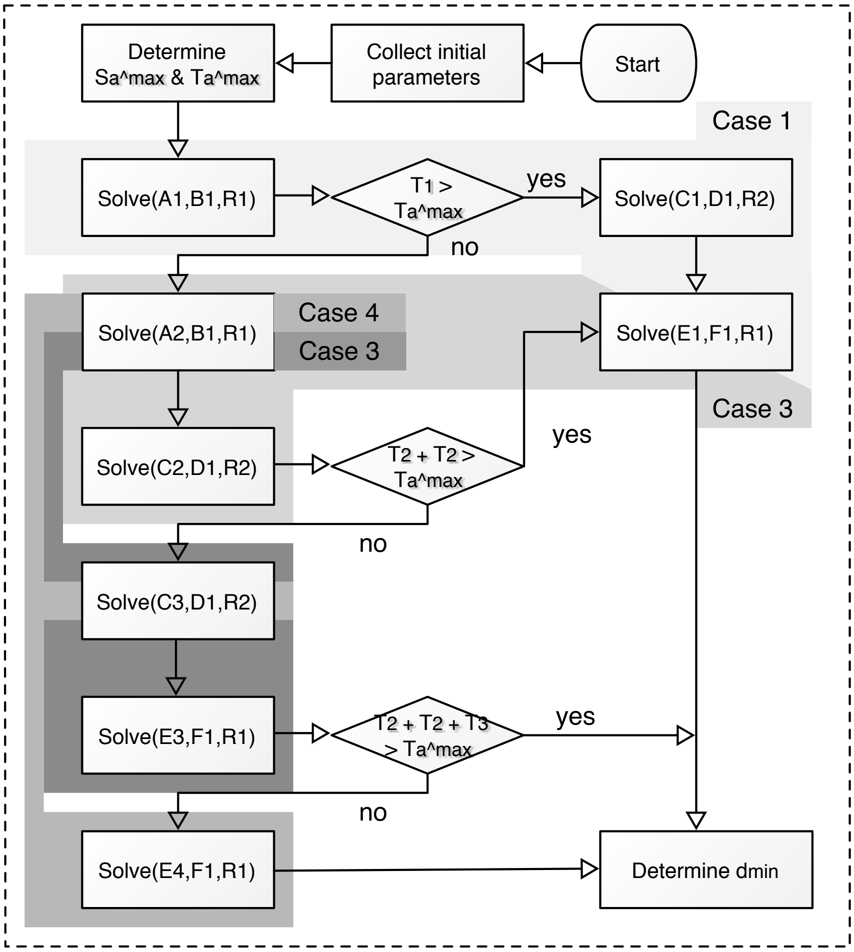

Figure 3.18: Flow diagram for determining d_{min}.

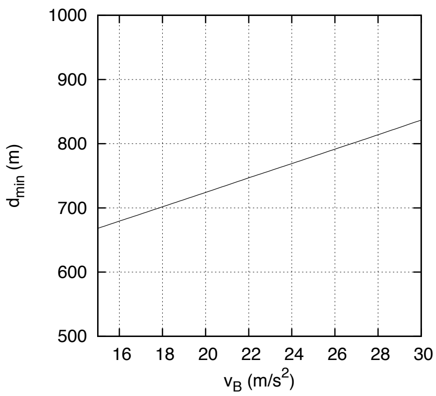

Figure 3.19: d_{min} as function of *Node B*'s velocity.

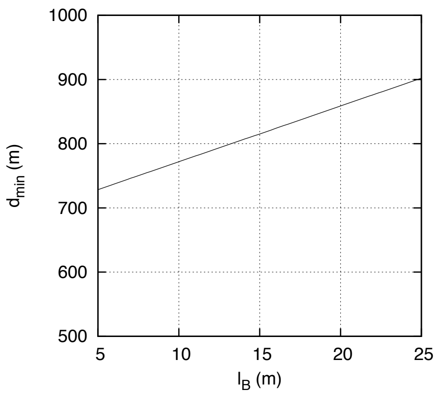

Figure 3.20: d_{min} as function of *Node B*'s length.

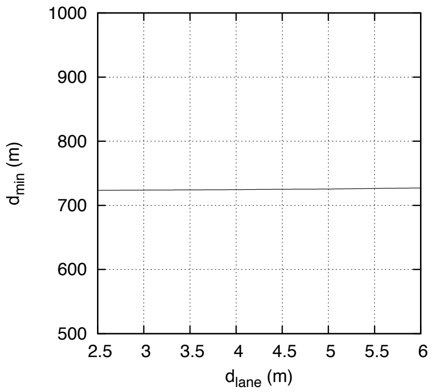

Figure 3.21: d_{min} as function of line width.

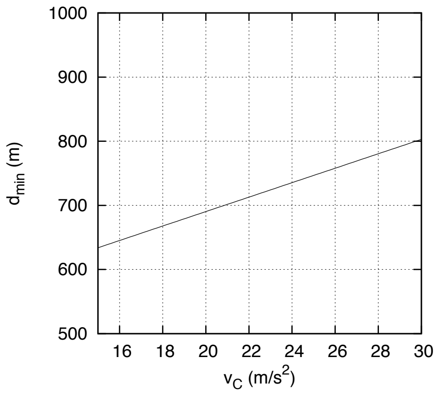

Figure 3.22: d_{min} as function of *Node C*'s velocity.

influence of *Node A*'s maximum speed v_A^{max}. A difference of just 2.2 m/s results in a variation of almost 200 m for d_{min}. This reveals a possible Achilles heel: beforehand v_A^{max} is unknown but seems to have a major influence on d_{min}. A solution could be given by actively supporting the driver to reach a predetermined overtaking-speed.

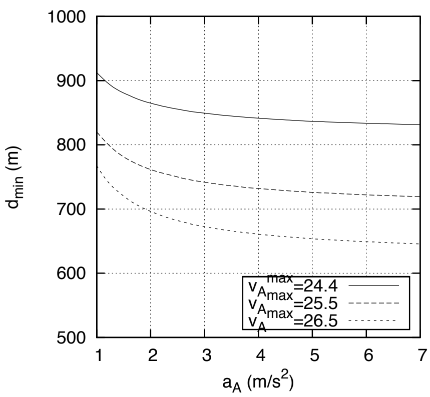

Figure 3.23: d_{AC} as function of *Node A*'s acceleration.

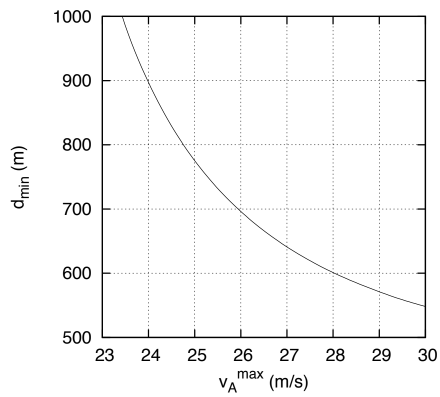

Figure 3.24: d_{AC} as function of *Node A*'s maximum velocity.

3.4.8 Discussion

This sections discusses some significant issues that have not yet been addressed.

Lack of traffic

Until now the existence of a *Node C* is assumed, but obviously the presence of this vehicle is not a certainty. In the occasion there is no vehicle approaching from the opposite direction, the system would be unable to have knowledge about unoccupied road sections ahead. This is an undesirable scenario because it would only allow the system to work when there is traffic approaching and thus a reduced chance for an overtaking possibility. Therefore it is required to know up to what distance the road ahead is clear. Knowledge about the lack of traffic is just as important as the discovery of new vehicles.

Information provided in advance

Figure 3.25 presents a scenario where *Node A* is informed that overtaking is impossible as *Node C* already has approached within close vicinity. When *Node C* has passed it takes some additional time to discover *Node D* and make new estimations. Better would be if *Node C* communicates in advance to *Node A* about the gap *D* towards *Node D*. Now *Node A*'s driver can be recommended to immediately start overtaking after *Node C* has passed. Hence, it is desirable to have information also about (the lack of) traffic behind a possible *Node C*.

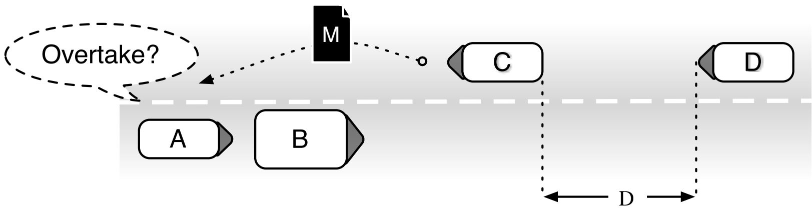

Figure 3.25: Information in advance.

Data integrity

Data integrity should be a key requirement as the information gathered by the ACOS is not of equal quality. A control mechanism must be introduced to provide the top-layer application with information about the data's accuracy. Based on this knowledge, the application can decide on how the acquired data should be interpreted. E.g. a quality assessment could be based on parameters such as the farthest known vehicle, level of connectivity or measurements on jitter.

Position logbook

It is valuable to maintain a logbook about the positions of discovered vehicles. Gathering and analysing this data can be applied to filter out malfunctioning nodes. E.g. a vehicle frequently changing positions in random directions can be marked as malicious. Such a node can however not be easily discarded. Its presence might be reason enough to prompt a negative advice on overtaking. In addition, maintaining a position logbook can also be applied to support QOS assessment.

Acceleration of other nodes

In contrast to the requirements for the approaching manoeuvre, the acceleration or deceleration of nodes *B* and *C* has been ignored until now. Since overtaking relatively consumes a lot of time, a discovered acceleration rate cannot be extrapolated over this entire period. Owing to this, node behaviour becomes unpredictable. A reliable advice on overtaking can therefore only be given when all involved nodes are conveying with a constant speed. Concluding, the other nodes' acceleration rates have to be taken into account for detecting unpredictable vehicle behaviour.

Unassigned communication bandwidth

Data contained by message M should be as compact as possible to remain some unused bandwidth that can be applied for future enhancements. E.g. it could be important to include knowledge about the other vehicle's blinkers. Although not applied in this research, an active blinker could be a valuable indication about a node's future movements.

3.4.9 Requirements

- Required knowledge about *Node A*: current position and velocity.
- Required knowledge about *Node C*: position, acceleration, direction, velocity, distance towards a possible *Node D* and a time stamp.
- Required knowledge about *Node B*: position, acceleration, velocity, length, speed, if there is traffic in front and a time stamp.
- Knowledge about what sections of the road are clear.
- Keep track of the other node's variation in speed.
- Message M latency: as low as possible.
- Minimal communication range: up to ~ 900 m for the scenarios as presented in Section 3.4.7.
- Broadcast mode: periodic.
- Communication type: unidirectional V2V.
- Throughout the whole manoeuvre the *TCC* had to be monitored by receiving new updates about *Node C*. This TCC should remain above 3 seconds.
- Support for QoS assessment.
- Unassigned bandwidth for future developments.

The minimal communication range exceeds values that are found in field measurements for the passing sight distance. An explanation for this high value could be the strict implementation of the recommended headways, *TTC* and human reaction delay. Incorporating these factors heavily increases d_{min} while in reality drivers don't strictly follow up these safety rules. Nevertheless, the ACOS should be able to guide the driver conform to these safety recommendations and thus be able to bridge a large span by means of wireless communication.

3.5 Requirements overview

This section gives a brief overview of important requirements for the ACOS system as derived from this chapter.

3.5.1 General requirements

The following general demands always have to be assured.

1. Adding a new node to the system should not require any human interaction.
2. System should explicitly not rely on any (fixed) infrastructure to work.
3. Should be scalable; has to work nationwide (information is disseminated through the network in sparse as well as dense network scenarios)
4. When broadcasting a PDU, it should fit in a single packet from the LLS.
5. Only use a minimal set of information from other nodes: data aggregation.
6. Processing power: should be able to perform all calculations and estimations in a fraction of time.

3.5.2 Message M

Message M has to contain the following data about it's creator at the time of creation.

1. Position.
2. Acceleration.
3. Velocity.
4. Vehicle length.
5. Time stamp.

Furthermore information about surrounding nodes and clear road sections has to be included. Also, some data space has to be left unassigned to support future enhancements.

3.5.3 Functional coverage range

From Section 3.3.9 and 3.4.7 can be concluded that the VANET should be able to, at least, exchange information over the following distances.

1. Approaching a slower vehicle: $\sim 450\ m$.
2. Overtaking an impeding vehicle with the accelerative manoeuvre: $\sim 900\ m$.

3.5.4 Monitoring

Several modules have to be included to perform the following tasks.

1. Position logbook.
2. Continues monitoring of the TTC towards *Node C*.
3. Continues monitor safety distance d_S when approaching the slower vehicle.
4. Detect and address malicious vehicles.
5. Keep track of empty road sections.

3.5.5 Abort overtaking

The overtaking manoeuvre has to be aborted in the following occasions.

1. Discovery of new opposing vehicle making overtaking impossible.
2. Sudden and unexpected changes in vehicle behaviour.
3. Discovery of malicious vehicle.

Chapter 4

ACOS Dissemination Protocol

This chapter describes the dissemination protocol that has been developed for this research to exchange messages between vehicles in the ACOS environment. Existing dissemination protocols (described in Section 1.6) are not specifically designed for revealing nodes far-ahead and focus on rapidly broadcasting emergency warnings. Therefore we decided to design a new dissemination protocol that specifically suits the ACOS. It was not in scope of this project to research alternative protocol designs. In other words, one approach has been designed and implemented in pursue to answer the research questions.

The methodology applied throughout the first sections is based on the readers [60] and [61]. First, Section 4.1 and 4.2 globally explain the service, after which Section 4.3 and 4.4 take a closer look at the system's buildings blocks and the different communication events respectively. Section 4.5 and 4.6 describe in more detail the actual message that is broadcasted by the vehicles. And finally, Section 4.8 and 4.9 describe two methods that can contribute to a higher service level: data extrapolation and data aggregation.

4.1 Basic service description

Figure 4.1 presents a simple overview of the ACOS Service (ACOS). All communication between the vehicles attending the service is performed over this service layer. Vehicle number 1 to N are provided with information on overtaking through their ACOS Service Access Points (AS). The depicted vehicles can be interpreted as the drivers, and the AS as being the user interface towards this driver / end-user.

In theory there is no limitation to the number of vehicles that can be supported by the ACOS. The service is scalable and can be deployed over vast areas, e.g. nation-wide. However, in practice the QoS might suffer

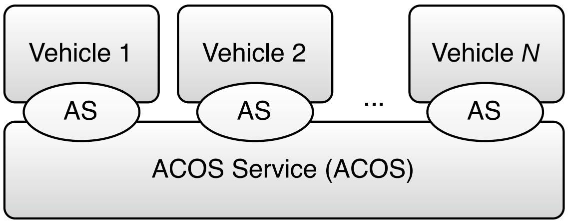

Figure 4.1: The ACOS Service.

in environments with a high density of vehicles. Also, as a result of the VANET's limited communication range, and due to the mobile nature of vehicles, the service will be geographically spread over isolated and ever-changing coverage areas.

All vehicles are served equally by the ACOS, there exist no high-priority vehicle or whatsoever. The ACOS provides by design an unreliable and connectionless service. As a consequence messages can get lost, become altered, and information is not necessarily delivered in chronological order.

4.2 Detailed service description

The ACOS has to rely on a Lower Level Service (LLS) to allow collaboration among the vehicles by means of wireless data exchange; the VANET embodies this LLS . In Chapter 2 was already chosen to rely on the IEEE 802.11p standard for wireless communication. Figure 4.2 shows the before presented service specification in more detail.

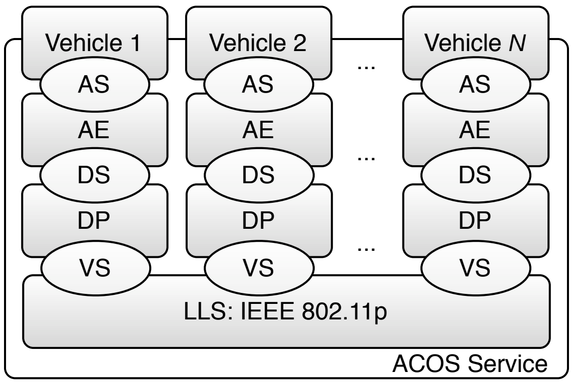

Figure 4.2: Detailed ACOS Service.

Again, every vehicle is connected to the service through their AS. New are the following entities: ACOS Application Entity (AE) and the ACOS Dissemination Protocol Entity (DP). The AE handles all application tasks; these include, but are not limited to: data interpretation and presentation. In fact, the AE handles all tasks that are required for the ACOS to provide information about overtaking, except for data gathering and dissemination operations.

These last mentioned tasks are the DP's responsibility, it communicates with the AE through their shared Dissemination SAP (DS). The DP broadcasts periodically information about its parent vehicle and recently discovered vehicles. Furthermore, it receives a similar information-set from neighbouring vehicles. For data exchange the DP relies on the underlying LLS, which is accessed through the VANET SAP (VP). The LLS (IEEE 802.11p) provides a connectionless and unreliable service.

From this point will only be focussed on the DP since this work's goal is to research the dissemination of data. Hence, this chapter will not elaborate on the AE's design; the requirements from Chapter 3 can provide a useful reference framework for its functioning.

4.3 Dissemination protocol entity

This section takes a closer look at the DP by describing its functional components. Figure 4.3 gives a structured overview of its building blocks together with their mutual relations. As earlier depicted in Figure 4.2, the DP bridges the application layer on top and the LLS layer underneath. What follows is a description of each DP component.

Car Info - contains static information about the vehicle that hosts this DP instance. It contains a unique identifier (ID) and information about the perimeter of the vehicle (length).

Vectors - stores vector instances created by *Vector Creator*. A vector contains the following properties: position, driving direction, velocity, acceleration and a time-stamp. The above application layer can request data from *Vectors* and thus has access to detailed knowledge about the vehicle's moving history. *Vectors* can only hold a maximum number of vector instances and applies a FIFO policy.

Vector Creator - periodically requests data from the *GPS module* to create new vector instances. This new vector is then stored in the *Vectors* repository. To detect and discard malicious moving patterns, the acquired data is compared to a selection of recent stored vectors. Every vector has a time-stamp which is provided by *GPS module* as well.

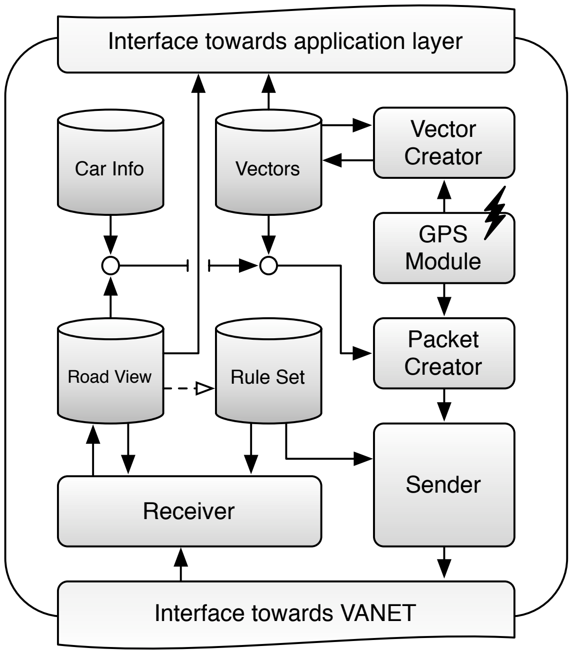

Figure 4.3: Dissemination Protocol Entity.

GPS Module - continuously determines the current position, driving direction, velocity and acceleration of the vehicle. Furthermore, it provides the *Vector Creator* and *Packet Creator* with accurate time information from the GPS signal. This mechanism assures time synchronisation among all vehicles.

Rule Set - contains a collection of predefined broadcasting settings. These are: the broadcast frequency, transmission power and the *time-span* of a vector. This *time-span* indicates how long data will remain valid after its creation.

Receiver - when the underlying VANET successfully has received a new message, it is passed on to the DP. The *Receiver* decomposes these message into smaller information chunks - vectors - about the discovered surrounding vehicles. The new acquired data is stored in, and validated against, the *Road View* repository. A new received vector is discarded when more recent data is already available from that specific vehicle. Also, received information about itself is immediately discarded.

Road View - repository for vectors received from surrounding vehicles. The data stored and made available by *Road View* shapes this vehicle's knowledge about the environment. It is accessed and analysed by the application layer to determine whether overtaking is advisable and/or to detect hazardous traffic situations. Data older than the time-span, as defined by *Rule Set*, is immediately removed from the repository. This assures that *Road View* does not contain out-dated information and thus an uncertain knowledge about the environment. The selected *life-span* is therefore of great influence of the system and is explained in Section 4.7.

Packet Creator - responsible for creating new messages that can be broadcasted by the *Sender*. Such a message contains the newest vector made available by *Vectors*, a footprint of the current data in *Road View*, information from *Car Info* and a time-stamp from the moment of creation. A detailed description of this message can be found in Section 4.5. *Packet Creator* continuously spawns new messages and stores them in a 1-sized buffer which is offered to *Sender*. The time provided by the *GPS module* is used for the creation of time-stamps.

Sender - periodically hands over messages to the VANET according to the broadcast frequency and the transmission power as defined by the *Rule Set*. The actual broadcasting is then handled by the underlying VANET. *Sender* is unaware whether a message has successfully reached its destinations or not; the LLS does not provide any delivery certainties.

The relation between *Road View* and *Rule Set* has not yet been addressed, in Figure 4.3 it is represented by the dotted arrow. At this stage is assumed that the parameters as defined by *Rule Set* have static values. However, the ACOS might perform better with a varying collection of settings that relate to different traffic environments. An intelligent DP should be able to dynamically adjust the *Rule Set* by analysing its *Road View*. Chapter X will further elaborate on this matter.

All vectors generated by the *Vector Creater* comply to the syntax as portrayed in (4.1). How this data is enclosed into a packet by the *Packet Creater* will be pointed out in Section 4.5.

$$\{Time, Position, Direction, Speed, Acceleration, Diameter\} \tag{4.1}$$

Both *Vector Creator* and *Packet Creater* apply time-stamps. It is important that information about a vehicle is always related to the exact point in time that the measurements were taken. E.g. it could occur that the *GPS Module* can't determine the vehicle's position - no new vectors are spawned - and therefore aged data gets re-broadcasted. In this scenario it would be undesirable that old data becomes related to the creation time of its encapsulating packet. This would inject the service with false information. Hence, vector time-stamps might - and will - differ from packet time-stamps. This design choice allows a more accurate determination of vehicle positions and DPs to better validate their received data.

4.4 Service Primitives

By design the ACOS Service's communication protocol is very uncomplicated as it only relies on the exchange of a single type of message. For this reason the VS only has to distinguish two kinds of Service Primitives (SP): *SendStat* for when status information is to be broadcasted and *StatInd* for when a message is received from the underlying VANET.

Figure 4.4 provides a trace for a simple broadcast scenario where only two vehicles (*DP 1* & *DP 2*) are connected by the VANET. Both DPs periodically initiate a *SendStat* SP according to their broadcast frequency. When the message is successfully delivered by the LLS, the *SendStat* will result in a *StatInd* event at all other vehicles in range. On the contrary, no *StatInd* will occur when the VANET fails to deliver the message. In Figure 4.4 *DP 1*'s second broadcast is unsuccessful; *DP 1* nor *DP 2* is aware of this communication error.

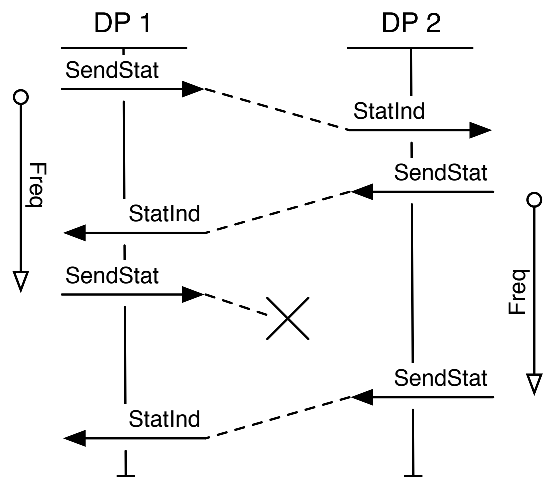

Figure 4.4: Broadcast trace for two vehicles.

4.5 Informal PDU Syntax

This section informally describes the message that is exchanged by the vehicles; this message is from now on referred to as the Protocol Data Unit

(PDU). Figure 4.5 shows the PDU's composition and how it is encapsulated by the IEEE 802.11p packet. What follows is a detailed description of each of the PDU's fields. Its design is based on two objectives: compliance with the requirements as defined in Chapter 3 and minimising the packet size without sacrificing any functionality.

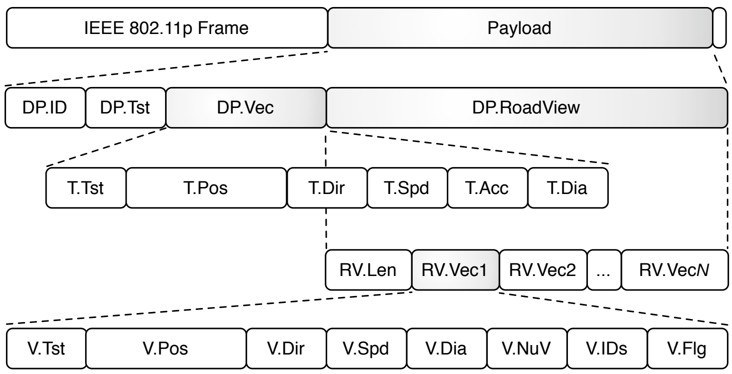

Figure 4.5: PDU frame.

DP.ID - The sender's DP identifier that allows other vehicles to map received PDUs and vectors to a specific vehicle. This ID is not registered and only serves to distinguish vehicles.

DP.Tst - Time stamp from the moment that the packet was created, based on GPS data. To reduce the packet size, the stamp is defined as the time in (ms) that has lapsed after the last full minute. As a result, the maximum value to be held by this field is $59,999\,ms$, which can be represented by 3 bytes.

DP.Vec - Contains the sender's vector - as earlier defined by (4.1) - and is arranged by the following sub-fields:

T.Tst - GPS-time at moment of the vector's creation; equally defined as the previous described time stamp $DP.Tst$.

T.Pos - The vehicles' X, Y and Z GPS co-ordinates at time $T.Tst$, given with an accuracy of one meter.

T.Dir - The vehicles' driving direction at time $T.Tst$, given by a value from 0° to 360° with step-size 2. As a result, $T.Dir$ is represented by an integer value from 0 to 180 that fits within a single byte.

T.Spd - The vehicle's velocity at time $T.Tst$, given by a product of $0.2\,m/s$. Because also $T.Spd$ is represented by a single byte, its maximum value is set to $50\,m/s$ (=$180\,km/h$). When $T.Spd$ is set to 51 m/s, this indicates that the vehicle's speed exceeds the selected scale.

T.Acc - The vehicle's acceleration at time *T.Tst*, given by a product of 0.1 m/s^2. The *T.Acc* field is represented by 7 bits that represent values up to 12.8 m/s^2 and a single bit to define whether its value is positive or negative. This results in a total covered acceleration range of $-12.8 \div 12.8\, m/s^2$.

T.Dia - The vehicle's perimeter represented by a circle with diameter *T.Dia* with position *T.Pos* as its centre. At this stage diameter *T.Dia* is given by the vehicle's length with an accuracy of 1 meter; the value is stored in a single byte.

DP.Roadview Foot print of DP's *Roadview* as described in Section 4.3, it is composed from the following sub-fields:

RV.Len The number of vector instances' that *DP.Roadview* contains, given by an integer that is stored by a single byte.

RV.Vec A single vector instance inside *Roadview*. Its sub-fields *V.Tst*, *V.Pos*, *V.Dir*, *V.Spd* and *V.Dia* are exactly defined as *T.Tst*, *T.Pos*, *T.Dir*, *T.Spd* and *T.Dia* respectively. Take note that *RV.Vec* does not carry a field for acceleration. Information about a vehicles' acceleration is only valid within very small time constrains, therefore is chosen to only broadcast this data to direct neighbours. The *V.Flg* field contains 8 bits that can be set as flags which remain unused up to this point. Remaining fields *V.NuV* and *V.ID* will be explained in Section 4.9.

As only 2^{16} unique IDs are available, it is required that ID reuse will be applied. Consequently, it might occasionally occur that two vehicles, assigned with the same ID, will inject the system with conflicting data. This will be filtered out by the DP since those vehicles will be detected as a single malicious node (being in two places at the same time).

Take note that the PDU only contains information that is required for the ACOS service. For real life deployment it might be desirable to add more fields for security purposes. One could think about including a Message Authentication Code (MAC) for protecting a message's data integrity and its authenticity.

4.6 Concrete Syntax

This section describes the before presented PDU in a formal way. For every field the starting point is given together its size; all field lengths are composed of multiples of 8 bits. In addition, Appendix C provides the ASN.1 notation for the PDU.

Table 4.1 presents a structured overview of the fields that were introduced in Section 4.5. A short description is given for each field, together with the type of data it holds, its range (when applicable) and the applied unity. E.g. a range of $0 \div 255$ with unity $0.5\,m$ indicates that the field is able to define values up to $255 \times 0.5 = 127.5\,m$ with an accuracy of $0.5\,m$.

Field	**Description**	**Notation**	**bits**	**Range**	**unity**
		Payload			
DP.ID	Identifier	Integer	16	$0 \div 2^{16} - 1$	numerical
DP.Tst	Time stamp	Integer	3×8	$0 \div 6 \times 10^4$	$1\,ms$
DP.Vec	Sender's vector	-	-	-	-
		DP.Vec			
T.Tst	Time stamp	Integer	3×8	$0 \div 6 \times 10^4$	$1\,ms$
T.Pos	Position	Degrees	2×16	-	-
T. Dir	Direction	Integer	8	$0 \div 180$	$2°$
T.Spd	Speed	Integer	8	$0 \div 255$	$0.2\,m/s$
T.Acc	Acceleration	Integer	7	$0 \div 128$	$0.1\,m/s^2$
		Boolean	1	-	$+$ or $-$
T.Dia	Diameter	Integer	8	$0 \div 255$	$1\,m$
		DP.RoadView			
RD.Len	#Vectors	Integer	8	$0 \div 255$	1
RD.Vec	Vector	-	-	-	-
		Rd.Vec			
T.Tst	Time Stamp	Integer	3×8	$0 \div 6 \times 10^4$	$1\,ms$
T.Pos	Position	Degrees	2×16	-	-
T. Dir	Direction	Integer	8	$0 \div 180$	$2°$
T.Spd	Speed	Integer	8	$0 \div 255$	$0.2\,m/s$
T.Dia	Diameter	Integer	8	$0 \div 255$	$1\,m$
V.NuV	#Vehicles	Integer	8	$0 \div 255$	numerical
T.ID	Identifiers	Integer	$X \times 16$	-	-
T.Flg	Flags	Boolean	8	$0 \div 8$	$1bit$

Table 4.1: PDU field descriptors.

As mentioned before, an ASN.1 notation for the PDU can be found in Appendix C.

4.6.1 PDU Storage Availability

In the requirements was stated that all information has to be broadcasted in a single packet. The maximum payload for a IEEE 802.11 packet is 2312 octects. This knowledge allows us to calculate the maximum number of vectors that can be transported by a single PDU. The obligatorily fields consume 17 bytes, plus 13 bytes for every vector in the *DP.Roadview* field. This gives

$$\begin{aligned} \#Vectors &< \frac{2312-13}{17} \\ &< 136, \end{aligned} \tag{4.2}$$

indicating that each packet can at most hold information about 135 surrounding vehicles.

4.7 Life span

As explained earlier in Section 4.3, every vector recorded by the *Road View* repository has a certain *life-span.* Its value is stored in the DP's *rule-set.* The *life-span* influences on how far data will be carried on within the system.

Say that *life-span* has a value of 10 seconds, this would imply that 10 seconds after the vector's creation it can still be passed on to another vehicle. The vehicle's data has now been conveyed over a relatively large time and distance. This could be desirable in some occasions, the vector's information can however also be regarded as being out of date. In 10 seconds the vector's creator has most likely moved to an entire other position. Still, a large *life-span* value allows information to be carried over large distances, which could help the ACOS by in advance discovering opposing vehicles.

A small value for *life-span* on the other hand reduces the number of vectors that is exchanged by the system. The 10-second scenario results in PDUs stuffed with (old) information. On the contrary, a 1-second *life-span* forces the ACOS to only exchange very recent discovered vehicles, limiting the packet size. Naturally this would stress the VANET to a smaller extent, but would also reduce the probability to discover a distant vehicle.

Concluding, a balance has to be found for *life-span* that doesn't introduce bulky PDUs, but still allows information to be carried over reasonable long distances. Chapter 5 presents ACOS performance figures for different values of the *life-span* variable.

4.8 Data Extrapolation

The more remote other vehicles are situated, the smaller the chance to retrieve information from these vehicles. Once two vehicles move out of each other's range, or when the VANET repeatedly fails to deliver a message, data extrapolation injects the ACOS with assumed new positions about the vehicle that *disappeared.* For this research, data extrapolation is performed by assuming the vehicle continues to move in a straight line. Given the position, speed and direction of the vehicle, it's expected new position can be determined along the road. E.g. a vehicle moves eastwards with a velocity of $20\,m/s$ and was last seen at position $x = 120\,m$, it's expected new position one second ahead in time would be $x = 140\,m$.

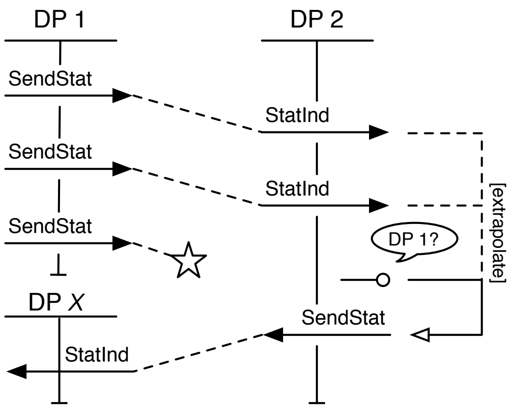

Figure 4.6: Trace for data extrapolation.

How this works is explained using Figure 4.6. In this scenario *DP 2* is frequently receiving PDUs from *DP 1*, but after a certain period *DP 2* stops receiving any new updates[1]. Without extrapolation this would indicate that *DP 1* will soon expire to exist in *DP 2*'s Road View. But with extrapolation enabled, *DP 2* calculates the assumed new position of *DP 1* and broadcasts this to its neighbours. New positions are calculated by extrapolating old positions and time stamps. This generated data is flagged - using the *V.Flg* field - as being non-genuine to allow other DPs to necessarily filter out this data. This could be desirable when actual real information (in)directly from *DP 1* is available.

Information about a vehicle's position, speed and direction should only be extrapolated for a certain maximum period of time. This is to overcome a difference between (re)broadcasted information and reality. The longer information is continued to be extrapolated, the bigger the probability for this information to be false. Without any time constraints, extrapolation could even introduce ghost vectors living on for ever in the *Road View*. Therefore we have chosen to only extrapolate genuine data and only for a maximum period of time that equals the *life span* of the entity that performs the extrapolation.

Figure 4.7 presents a schematic overview for the approach taken for data extrapolation. The figure shows that points out that a minimum number or 3 vectors is required in order to extrapolate. This number is chosen

[1]The first periodical broadcasts by *DP 2* are removed from the figure for keeping a clear overview.

because it gives 3 measurements to extrapolate, which should introduce a certain level of accuracy and still allows hard-to reach nodes to be taken into account.

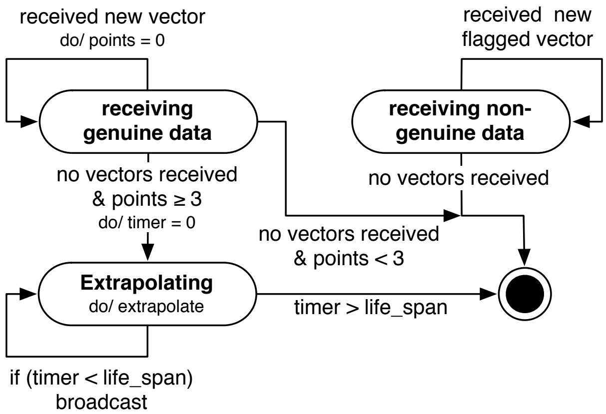

Figure 4.7: State machine for data extrapolation.

Data extrapolation might increase the visibility of remote vehicles and fill up missing information about hard to reach road sections. In Chapter 5 will be determined whether this approach increases the ACOS' ability to detect oncoming vehicles.

4.9 Data Aggregation

According to the system's description earlier in this chapter, information about every known vehicle - thus registered in *Road View* - is broadcasted by means of a PDU. In the system requirements (Chapter 3) it was stated that all data has to be broadcasted in a single packet, insinuating that the payload in the IEEE 802.11p packet should be able to transport all data at once. When surrounded by a large number of vehicles it might become impossible to fit all data within a single VANET packet. Not only is the payload capacity limited, we also stated that information should be transported as compact as possible.

Vector aggregation provides a method to effectively reduce the required data to be transmitted. To asses whether an overtaking manoeuvre is sensible, one does not require to know if just a single vehicle or an entire platoon is approaching from the other direction. Hence, information about clusters of vehicles with matching behaviour can be summarised by grouping them.

Figure 4.8 shows how three vectors are aggregated into a single vector instance. The left and right environment present the vectors before and after aggregation respectively. Three vehicles driving close to each other and displaying similar behaviour - each with their own location and diameter - are merged into a bigger area/vector with a new centre position and perimeter. This new shape now represents the entire group of cars.

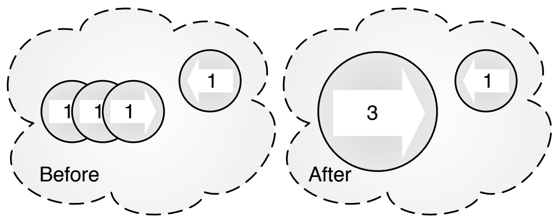

Figure 4.8: Aggregation from 3 to 1 vector instance(s).

The PDU fields labelled as *V.Nuv* and *V.IDs* have not yet entirely been discussed. Field *V.Nuv* contains the number of vehicles represented by the vector. Ordinarily this field would contain a value of 1, but in Figure 4.8's scenario it holds the number 3. The other field, *V.IDs*, contains all DP identification numbers belonging to the vehicles in the grouped vector. This is required since vehicles might receive both aggregated and genuine information about an identical vehicle. The application of these fields allow each vector instance to describe the behaviour of multiple vehicles.

Aggregation is a challenging approach to reduce the amount of transmitted data, but also introduces a higher level of complexity to the system. Examples of issues are how to determine the direction and speed of the group, and how to handle the possible conjunction of groups. Although this thesis does not take aggregation any further into consideration, the PDU is intentionally designed to support future system enhancements concerning this matter.

‘

Chapter 5

Performance Evaluation

As part of this research, a simple network simulator has been developed to observe the dissemination protocol's behaviour. The simulator - implemented in Java - is specifically designed to determine certain ACOS metrics. Main goal is to determine the influences of the broadcast frequency, the *time-span* and data extrapolation on the following properties:

- the accuracy of the road-view;
- the number of vectors in each PDU;
- the obtained degree of vision;
- and the number of colliding packets in the VANET.

As a reminder: *road-view* refers to the image of the road as it is created by the ACOS, *vision* to the distance from the vehicle to the outer edge of the road-view, and *time-span* is the time data remains valid after creation.

This chapter is structured as follows: Section 5.1 describes the approach for simulating VANET behaviour, Section 5.2 presents the vehicle mobility model and finally Section 5.3 presents the found simulation measures.

5.1 Simple communication model for 802.11p

A simple communication model is designed to simulate VANET packet broadcasts. This model is based on the works found in [62] and [63]. As will be explained throughout the chapter, some calculations are enhanced compared to those approaches. In addition, more suitable values are chosen for a selection of parameters. The resulting communication model is therefore expected to better suit this research.

5.1.1 Radio channel characteristics

Radio propagation is influenced by a large number of factors, these include: the selected frequency band, signal bandwidth, propagation environment, node mobility and antenna characteristics. E.g. for VANETs something trivial as antenna placement has an impact on the radio channel properties.

Influences on the radio signal can be interpreted as a combination of *path loss* and *small-scale fading*. The first mentioned estimates the mean signal strength for an arbitrary distance between a sender and receiver. In contrast, *small-scale* fading allows detailed modelling of signal strength fluctuations over very short periods of time. These fluctuations typically result from multi-path propagation and node movement [64].

Studies have shown that effects from path loss and small-scale fading are influenced by the existence of a direct Line of Sight (LOS) between the sender and receiver. With LOS the *two-ray path loss* model allows to determine channel behaviour, since the received power is dominated by the LOS and ground reflection path. When no LOS exists (NLOS), the *long-distance path loss* model can be employed [62].

The NLOS scenario implies the existence of obstacles between the sender and receiver. This could be due to a heavy traffic load or environment characteristics. LOS can be assumed for sparse populated roads and communication between adjacent nodes.

5.1.2 Two-ray path loss model

For this thesis only LOS communication is considered because simulations are performed by modelling an obstacle-free straight road with a moderate traffic load. Consequently, the *two-ray path loss* model is applied to determine the perceived signal strength at the receiving nodes. In [62] this model is simplified to (5.1), assuming equal sender and receiver antenna heights and entirely neglecting any antenna gain.

$$\begin{aligned} P_r(d) &= \frac{P_t}{(4\pi)^2 \left(\frac{d}{\lambda}\right)^\gamma} \left[1 + \eta^2 + 2\eta cos\left(\frac{4\pi h^2}{d\lambda}\right)\right], \\ & \quad with\ \lambda = \frac{c}{f}. \end{aligned} \tag{5.1}$$

Symbol P_r denotes the power received, P_t is the power transmitted, λ is the wavelength of the propagating signal, γ is the path loss exponent, η is the reflection coefficient of the ground surface, h is the distance from this surface to the antenna and finally d is the distance between the sending and receiving node.

For this thesis P_t is fixed to $33dBm$, which is the maximum allowed transmission power for regular IEEE 802.11p communication. The reflection coefficient η is, for non-conductive and non-ferromagnetic materials, a real number between -1 and 1. For this thesis the reflection coefficient is fixed to $\eta = -0.7$ (asphalt), which is adopted from [62]. The path loss exponent γ usually has a value somewhere between 2 and 4, where 2 represents propagation in free space and 4 is for lossy environments. In [62] and [63] was selected $\gamma = 2.4$ for VANET communications. This value seems rather optimistic, for out-door suburban areas a range of $2.5 \div 3.5$ is usually taken into account. To be on the safe side - and not entirely neglecting [62] and [63] - this work assumes $\gamma = 2.8$. Finally, since the VANET operates on 5.9 GHz, the signal wavelength is set to $\lambda = 5.08 \times 10^{-2} m$.

Figure 5.1 presents the received power as a function of the distance between the sender and the receiver for $\gamma = 2.4$, $\gamma = 2.8$ and $\gamma = 3.2$. It is easily observed that the path loss exponent has a reasonable impact on the signal's attenuation. Over a distance of $100\,m$ there is a difference of almost $20\,dBm$ between $\gamma = 2.4$ and $\gamma = 3.2$. This indicates that the ACOS' performance level is highly influenced by environment characteristics.

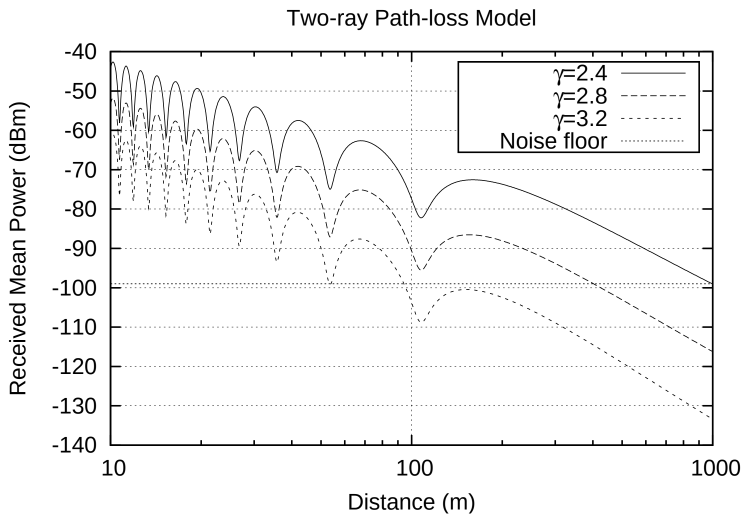

Figure 5.1: Received mean power derived from Equation 5.1.

5.1.3 Signal to noise ratio

In (5.2) a simple method is given to determine the Signal to Noise power Ratio (SNR). The signal strength of the receiving packet is denoted by S, while $\sum I$ is the sum of all interfering packet signal strengths and N_b represents an always presents background noise.

$$\frac{E_s}{N_0} = \frac{S}{\sum I + N_b} \tag{5.2}$$

When taking into account the effects introduced by the cyclical prefix attached to each OFDM symbol, the SNR has to be reduced by a certain factor α. This is due to the fact that the cyclic prefix does not contain any data. According to [62] the SNR has to be reduced by $\alpha = 0.8$ for IEEE 802.11p PHY, resulting in (5.3). See [62] and [65] for more information on this matter.

$$\frac{E_s}{N_0} = \alpha\left(\frac{S}{\sum I + N_b}\right) \tag{5.3}$$

Equation 5.4 is applied to determine the background noise N_b, also referred to as the noise floor. Parameter BW denotes the bandwidth, in this case $10MHz$, and the Noise Figure (NF) is the degradation of the signal caused by components at the receiver side.

$$N_b = -174 + 10\log(BW) + NF \tag{5.4}$$

Assuming that $NF = 5dBm$ gives a noise floor of $-99dBm$ after applying (5.4). This is more flexible compared to $N_b = -95dBm$ as is assumed in [63] and [62]. When the interference level exceeds the received packet signal, thus when the $SNR < 1$ and/or $S \leq -99dBm$, the packet will be instantly dropped by the simulator. When $SNR > 1$ and S $99dBm$, then packet will be successfully delivered. For the sake of simplicity, this check is only performed at the nodes themselves. Figure 5.1, already introduced earlier, shows how the noise floor relates to the received power level.

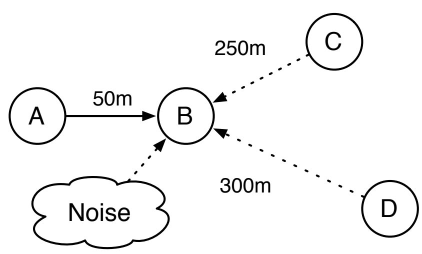

Figure 5.2: Example SNR scenario.

Figure 5.2 provides an example scenario where Node B is receiving a packet from Node A. Concurrently, the remote situated Nodes C and D introduce interference signals by utilising the channel as well. Combining (5.1), (5.3) and (5.4) allows to determine the SNR for Node B, with $P_t = 33dBm$, $\gamma = 2.8$, $\eta = -0.7$, $N_b = -99\,dBm$, and operating frequency $5.9\,Ghz$.

$$\frac{E_s}{N_0} = \alpha\left(\frac{P_r(50)}{P_r(250) + P_r(300) + N_b}\right) \approx 8.45 \tag{5.5}$$

Figure 5.3 shows how the SNR degrades when the distance towards the receiver increases; please note the logarithmic scale. As indicated before, the SNR has to be greater then zero for a successful transmission. This means that around $100\,m$ successful communication is unlikely, since the SNR is very close to zero, and beyond $300\,m$ no data exchange is possible at all. These findings correspond to the allowed extended communication range up to $335\,m$ for vehicle to vehicle co-operative collision warnings.

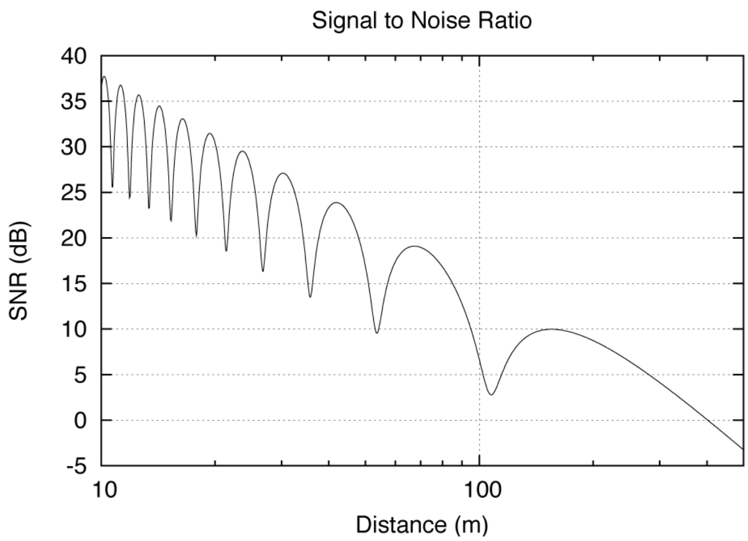

Figure 5.3: SNR over distance.

5.1.4 Bit error probability

This section applies the same approach as in [66] to determine Bit Error Rates (BER) for the 802.11p PHY layer. Calculations are based on the SNR as defined in the previous section. As listed in Table 5.1.4, 802.11p employs the following modulation schemes: Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16 and 64 Quadrature Amplitude Modulation.

Data rate	3, 4.5, 6, 9, 12, 18, 24 and 27
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Subcarriers	52
OFDM symbol duration	8μs
Guard time	1.6μs
FFT period	6.4μs
Preamble duration	32μs

Table 5.1: Selection of 802.11p characteristics

Function Q, which can be found in [67], is given by (5.6), is required to determine the BERs for all modulation schemes. $Q(x)$ is related to the complementary Gaussian error function by $Q(x) = \frac{1}{2}erfc\left(\frac{x}{\sqrt{2}}\right)$.

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{\frac{-t^2}{2}} dx. \tag{5.6}$$

The symbol error probability for an M-ary QAM can be estimated by applying (5.7) and (5.8). Results from P_M can then be used to to determine the bit error probability for QAM by applying (5.9).

$$P_M = 1 - (1 - P_{\sqrt{M}})^2, \tag{5.7}$$

$$P_{\sqrt{M}} = 2\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3}{M-1}\frac{E_s}{N_0}}\right), \tag{5.8}$$

$$P_b^{QAM} = \frac{1}{log_2 M} P_M. \tag{5.9}$$

For QPSK the symbol error probability is given by (5.10), and the bit error probability by (5.11)

$$P_{QPSK} = 2Q\left(\sqrt{\frac{E_s}{N_0}}\right)\left[1 - \frac{1}{2}Q\left(\sqrt{\frac{2E_s}{N_0}}\right)\right], \tag{5.10}$$

$$P_b^{QPSK} = \frac{1}{log_2 M} P_{QPSK}. \tag{5.11}$$

The bit error probability for BPSK modulation is given by (5.12), which is equal to its symbol error probability.

$$P_b^{BPSK} = Q\left(\sqrt{\frac{2E_s}{N_0}}\right). \tag{5.12}$$

5.1.5 Packet error probability

Knowledge about the BERs for the different modulation schemes is now applied to determine the corresponding Packet Error Ratios (PERs). Evaluation of the PER is however not straight-forward since bit-errors usually occur in bursts and convolutional coding allows error recovery. Nevertheless, a very simple approach is chosen for determining the PER. The probability for a packet error is given by the chance that one of the bits in the packet is flipped:

$$P_e = 1 - (1 - P_b)^{8L} \tag{5.13}$$

where P_b is the corresponding BER and length L represents the number of bytes in the packet's payload. Hence, the bigger the packet, the higher the probability for a packet error to occur. Figure 5.4 presents the PER as function of the SNR.

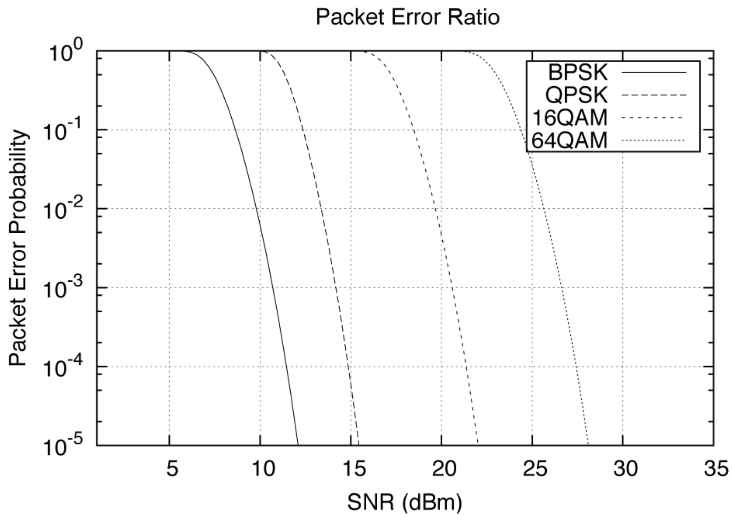

Figure 5.4: PER for $L = 200$.

Without any doubt these findings can be regarded as disputable since code rates are not taken into account. Better performances are expected to be achieved in a real environment. Though, according to these findings BPSK modulations is selected to be most suitable for the ACOS. BPSK has a lower throughput, introducing some delay compared to the other modulation techniques, but is more robust and allows to cover a broader range.

Figure 5.5 presents the expected PER in relation to the distance between the sender and receiver. Up to a $100\,m$ almost no packets will be altered due to radio characteristics. From that point up to about $125\,m$ no communication is available, since the PER reaches $P_e = 1$, after which the PER drops again and then gradually returns $P_e = 1$. Also, the covered distance by the VANET improves substantially for smaller payloads. This indicates that a smaller packet size is favourable for a better service.

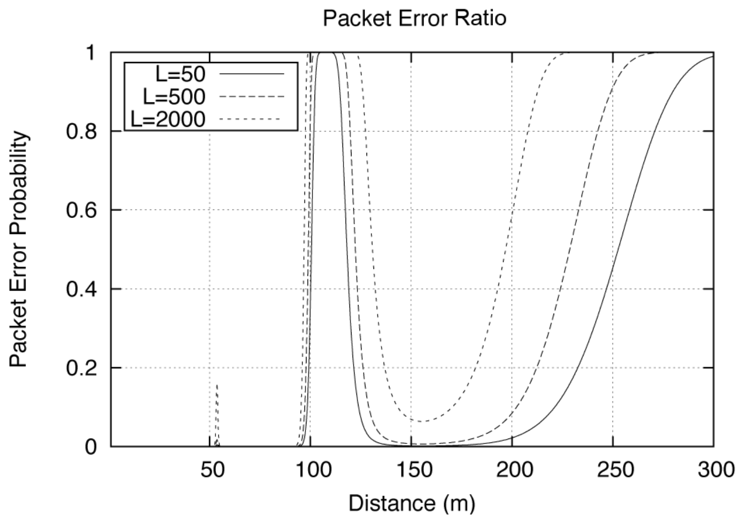

Figure 5.5: BPSK PER for different packets sizes.

5.1.6 Media access control

The IEEE 802.11p MAC layer was earlier introduced in Chapter 2. This section will now look more closely at how this layer operates and how it is implemented in the simulator.

IEEE 802.11p makes use of the Enhanced Distributed Channel Access (EDCA) mechanism which was originally designed for the 802.11e amendment. EDCA applies Listen Before Talk (LBT) and a random back-off time before the medium will be accessed after it was detected to be idle. This mechanism prevents that waiting nodes will access the medium simultaneously when it's available again.

The back-off time BT is composed from a fixed and a random selected waiting time. Both these times are expressed by a number of time-slots; each slot has a duration of $8\mu s$. The fixed waiting time is given by the Arbitration Inter-frame Space Number (AIFSN), while the random waiting time is randomly drawn from a Contention Window (CW). Initially, the size for the contention window is given by the parameter CW_{min}. See 5.14 for a clear overview of these rules with $rand()$ being a random function with a uniform distribution on the range $[0, 1]$.

$$\begin{aligned} BT &= (CW \times rand() + AIFSN) \times 8\mu & (5.14)\\ & \quad with\ CW_{min} \leq CW \leq CW_{max} & \\ CW_{new} &= 2 \times (CW_{old} + 1) - 1. & (5.15) \end{aligned}$$

As long as no activity is detected in the channel, a back-off counter is set to BT and will be decremented with a single time-slot each time. Whenever activity is detected, the counter is paused and only reactivated again when the channel has become idle once more. The node is allowed to transmit when the counter reaches zero. In case the transmission fails, the CW will be renewed, unless CW_{max} has already been reached [68].

EDCA provides prioritisation by utilising a set of distinct channel access parameters for different service categories. These categories are: Background (AC_BK), Best Effort (AC_BE), Voice (AC_VO) and Video (AC_VI) traffic. Table 5.1.6 gives an overview for these parameter sets.

AC	CWmin	CWmax	AIFSN
AC_BK	15	1023	9
AC_BE	7	15^2	6
AC_VO	3	7	3
AC_VI	3	7	2

Table 5.2: EDCA channel access parameters.

For the ACOS it is required that data is continuously exchanged between vehicles and preferably should not interfere too much with other ongoing communications. Since the ACOS introduces an always present data-flow, the background priority (AC_BK) is selected as being most suitable. A major drawback of this choice is that - when many data exchanges occur - the ACOS service might suffer from not being able to access the medium.

Summarising, when the ACOS has created a packet to be sent, the MAC entity acts according to the following instructions for broadcasting:

1. Start listening to the desired channel.

2. If the channel is idle (no active transmitters are detected), wait for the predefined AIFSN back-off time followed by a random selected back-off time within the contention window. This is done by counting down until the counter reaches zero.

3. In case the channel becomes occupied (at least one active transmitter is detected), then pause the counter until the channel become idle again.

4. If the counter reaches zero, then broadcast the packet. In case the transmission fails because another signal is detected, the CW has to be renewed and the counter reset to this CW_{min}[1] .

Figure 5.6 visualises the above described procedure by a Finite State Machine (FSM). Take note: as earlier described in Chapter 2, the 802.11p VANET relies on the CSMA/CA mechanism for MAC. This indicates that once a node starts broadcasting a packet, it is unable to detect any collisions or interfering signals. The mechanism also lacks any overhead messages for clearing the channel or sending acknowledgements.

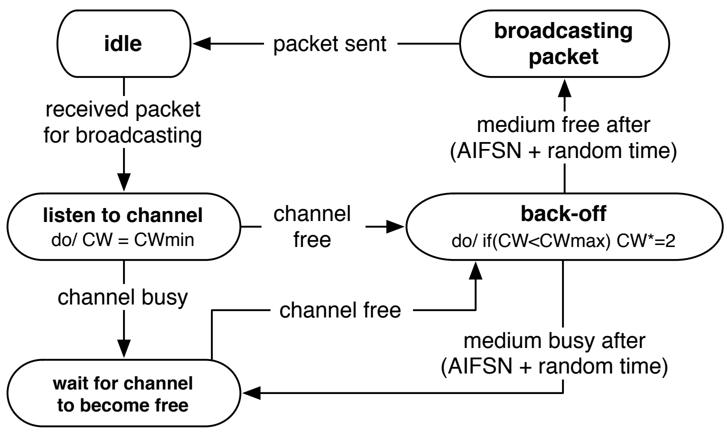

Figure 5.6: Simple FSM for IEEE 802.11p MAC .

[1] This is erroneously implemented in the simulator as during broadcast it is not possible to detect other signals. Due to very a small broadcast periods per node, it is not expected this design error significantly influences the simulation results.

5.1.7 Discussion

This section lists several issues that work both for and against the selected approach to model the IEEE 802.11p PHY and MAC layers. To start with, the following matters can contribute to better networking performances.

- Error-correcting codes are not taken into account for determining the PERs. This technique significantly reduces the number of packet errors.
- Any antenna gain is neglected for determining the received signal strength P_r by means of the two-ray model. Such gain improves the perceived signal strength and thus has a positive effect on the PER and communication range.
- The mobility model is based on a straight road with a traffic flow in two directions. Neighbouring vehicles on nearby or crossing roads are not considered. Such vehicles could function as intermediate hops, increase the level of connectivity and contribute to a broader coverage range.

In contrast, the following issues can result in reduced networking performances.

- The loss exponent is fixed to $\gamma = 2.8$, which represents an environment with a low number of obstacles. A large vehicle - like a lorry - or the presence of buildings could have a negative influence on this exponent, with as result a lower coverage range for the ACOS.
- The lowest EDCA channel access priority is selected for MAC, namely AC_BK. Throughout the simulations no higher priority traffic is inserted that competes for channels access. Nor is any other traffic inserted at all. In a real environment the ACOS service might have to compete with other data traffic, resulting in lower service level.

Because IEEE 802.11p is due in 2009 and currently no networking equipment has been manufactured, no real life measurements can be obtained for its networking performances. The availability of such data would allow much better predictions for VANET applications. Hence, results obtained in this chapter have to be taken hypothetically and seen a basic tool to predict the dissemination protocol's behaviour.

5.2 Mobility models

We selected to model a straight road section since it is most suitable for analysing the ACOS protocol. Modelling such a road has two main advantages: it is relatively easy to model and more important, it embodies the most demanding scenario for data dissemination. E.g. a scenario where nodes are moving on a curved road would be less stressing for the VANET, since shorter distances are to be covered by means of wireless communication. Or, modelling a network of roads would allow neighbouring nodes from other roads to function as intermediate hops. Figure 5.7 depicts the model environment.

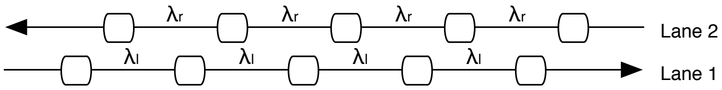

Figure 5.7: Simple mobility model.

New vehicles enter the road with intervals λ_l and λ_r from the left and right side respectively. When a vehicle reaches the other end of the road, its network interface is no longer simulated. Hence, a lower connectivity is experienced on the outer regions of the simulated area.

For both lanes the vehicles' speed is determined by a Gaussian distribution, the simulator allows to set the expected car velocity (μ_l & μ_r) and its standard deviation (σ_l & σ_r) for the left and right side respectively. Naturally, a $\sigma = 0$ value will result in all vehicles conveying at the same speed on that specific lane.

When a vehicle approaches a slower vehicle upfront, it will adjust its velocity to the vehicle ahead and automatically keep a $2\,s$ safety distance. The imposed vehicle will not be overtaken, over time this will result in a platoon behind the slow conveying vehicles.

An alternative and more challenging mobility model is depicted by Figure 5.8. The numbers between the vehicles denote the time in seconds between them. All vehicles - on both lanes - convey with an equal velocity of $v = 22\,m/s$. Three platoons are inserted into *Lane 1*, while for *Lane 2* every 30 seconds a new car is spawned.

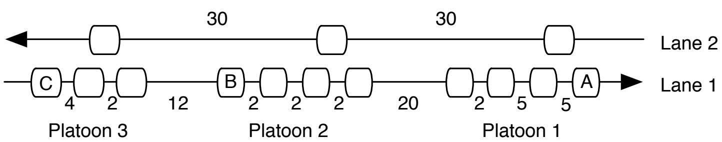

Figure 5.8: Advanced mobility model

The vehicles on *Lane 2* are - due their separation - unable to directly communicate with each other. Same holds for *Platoon 1* and *Platoon 2* since their mutual distance is too large. *Platoon 2* and *Platoon 3*, separated by

$12 \times 22 = 264\,m$, have a low but existing probability to exchange packets.

During simulations the focus will be on the vehicles marked as *A*, *B* and *C*. Monitoring *Vehicle A* allows to determine what information a vehicle upfront, thus without any vehicles ahead on *Lane 1*, is able to gather. Second, *Vehicle B*, being stuck behind *Platoon 2*, might indirectly receive information from the platoon in front. A vehicle driving on *Lane 2* could occasionally function as a bridge between these platoons, highly increasing *Vehicle B*'s level of vision. The same holds for *Vehicle C*, which in this scenario might receive information from one or maybe even two platoons ahead.

The simple mobility model is used to research the protocol's performance on averaged out traffic scenarios, e.g. based on traffics counts by a local government. The advanced mobility model allows to focus on a more detailed overtaking scenario by simulating three platoons on a sparse populated road section. Therefore this model is more appropriate for making statements concerning the ACOS' feasibility.

5.3 Simulation results

This section presents the simulation results as they were obtained by applying the two mobility models. If required, Appendix A gives a brief description of how the simulator works and what functions it provides.

5.3.1 Simulation settings

Table 5.3 summarises all the parameters that have been introduced so far, together with their corresponding selected values. These values were fixed for all the simulations that were performed for analysing the ACOS dissemination protocol.

5.3.2 Simulation with the simple mobility model

The simple mobility model is not applied to determine the ACOS' performance in overtaking scenarios. Its purpose is merely to show how information is able to traverse down roads with a high density of cars. Only a single scenario is taken into consideration, its simulation settings are listed in Table 5.4.

Figure 5.9 shows all car positions for the time domain $[0 : 200]\,s$. It is easily observed that several cars are conveying with a lower speed than others. As a result several platoons are formed.

From Figure 5.9 we can also conclude that communication is not always possible between all vehicles. Several gaps outreach the distance of $250\,m$ that is required to exchange messages by means of the underlying VANET. E.g. such a gap is found at $t = 118\,s$ on the road section $[1100 : 1500]\,m$.

Parameter	**Symbol**	**Value**
Radio Characteristics		
Reflection coefficient	η	0.7
Loss exponent	γ	2.8
Wave length	λ	$5.08 \times 10^{-2} m$
Transmission power	P_t	$33\,dBm$
Noise floor	N_b	$-99\,dBm$
Antenna height	h	$1.65\,m$
Modulation	-	BPSK
Data rate	-	$3Mbit/s$
Preamble duration	-	$32\mu s$
Media Access Control		
Fixed back-off time	AIFSN	$9 \times 8\mu s$
Initial size CW	CWmin	$15 \times 8\mu s$
Maximum size CW	CWmax	$1023 \times 8\mu s$

Table 5.3: Overview for simulation settings.

Parameter	**Value**
Car arrivals left	$\lambda_l = 7\,s$
Car arrivals right	$\lambda_r = 20\,s$
Avg. speed	$\mu_l = \mu_l = 22\,m/s$ & $\rho = 2\,m/s$
Length of road	$2000\,m$
Broadcast frequency	$5\,Hz$
Vector *Life-span*	$2000\,ms$
Simulation duration	$200\,s$

Table 5.4: Scenario for the simple mobility model.

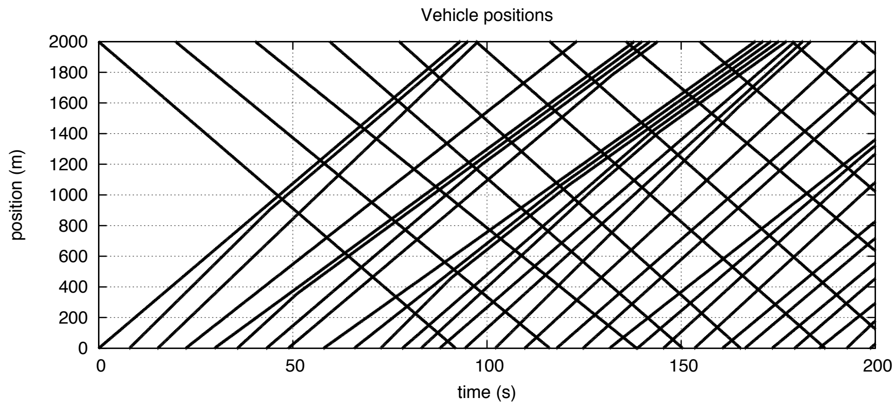

Figure 5.9: Vehicle positions for this scenario.

For one of the vehicles the road-view repository is plotted in Figure 5.10. Each dot represents a vector that was received and processed by this car's ACOS instance. It also includes the vectors that were created by this vehicle itself. The selected vehicle enters the road at time $t = 72\,s$ on position $x = 0\,m$. The communication gaps, as discussed above, are clearly visualised by this figure.

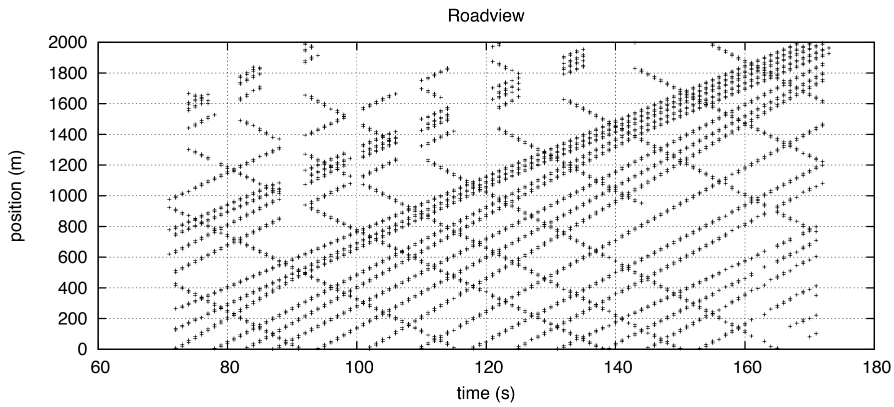

Figure 5.10: Roadview for one the cars.

For each single car the maximum level of vision was stored for every second throughout the entire simulation. If for vehicle i at time t the furthest known car - that is driving in opposite direction - is situated $800\,m$ ahead, then the maximum vision for vehicle i at time t is set to $800\,m$. If no other car was detected, the furthest know car was set to $0\,m$. Figure 5.11 presents for both lanes the maximum level of vision for all vehicles throughout the time domain $[10 : 200]\,s$

The maximum possible vision that can be reached diagonally declines when a car moves towards the end of the simulated road. If a car is positioned at $x = 500\,m$, then its vision cannot reach a value higher then $1500\,m$. Figure 5.11 show that sometimes new spawned vehicles are able to detect cars at the other end of the road within a very short moment of time. Only then values up to $2000\,m$ can be measured.

For every single PDU that was created during the simulation, the number of vectors is plotted to Figure 5.12. With this scenario no more than 19 vectors are broadcasted at a time, whereas the payload is capable of carrying up to 135 vectors. One could conclude that no violation occurs. This assumption is however biased as the simulated road never hosts more than 19 vehicles.

In very dense areas, such as cities, the maximum of 135 cars will easily be violated. In these circumstances there is a very small probability that communication gaps will occur. Setting a very small information *life-span*

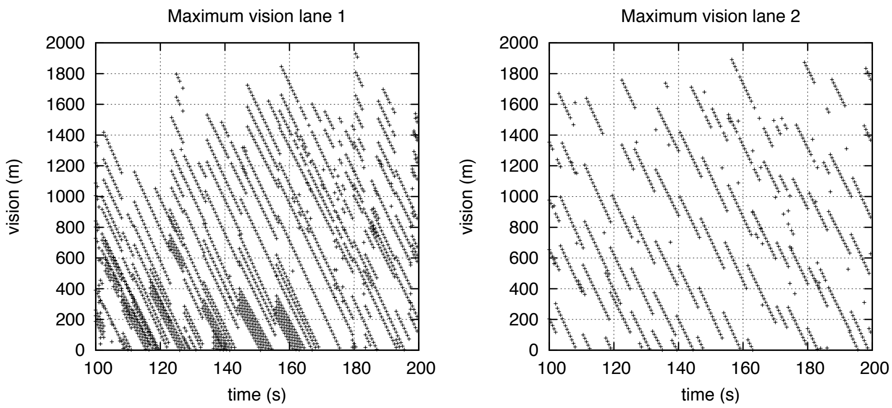

Figure 5.11: Maximum vision for vehicles in both directions.

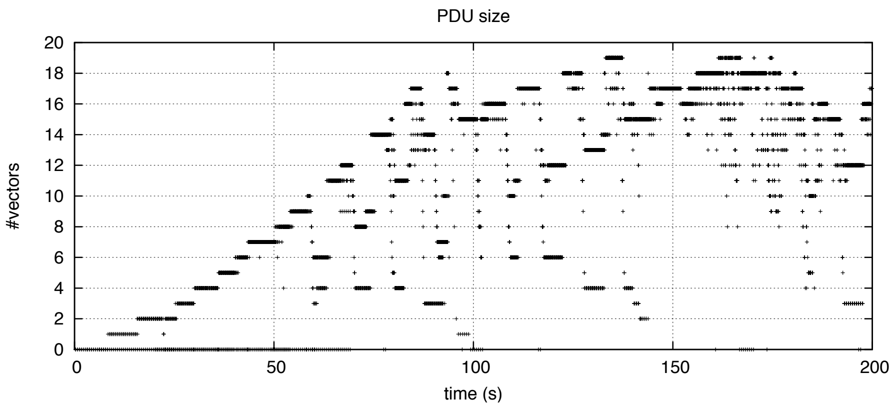

Figure 5.12: The number of vectors inside each broadcasted PDU.

could be a solution to this. That said, the ACOS is not designed with those environments in mind.

The MAC layer applies CSMA/CA and thus will not broadcast any packets unless the channel is available. This does not insinuate that packets cannot collide. During the transmission the vehicle is on the move and could possibly drive into an area where another vehicle is broadcasting as well. The simulator, as a monitoring entity, keeps track of the number of such events throughout a simulation run.

For this and all other scenarios no single collision was encountered. This can be explained by the fact that the channel is hardly occupied. Only a small number of nodes access the channel for sending at most one packet at a time.

It can be concluded that, for this particular scenario, the ACOS dissemination protocol allows to monitor traffic far up ahead. This simple scenario does however not give sufficient insight into what extent the protocol is applicable to overtaking manoeuvres. Non of the determined gaps between the vehicles was big enough to perform an overtaking manoeuvre. Due to the high density of vehicles neither did a possible false positive occur.

5.3.3 Simulations with the advanced mobility model

The advanced mobility model was earlier introduced by Figure 5.8 on page 80. All vehicles - on both lanes - convey with an equal velocity of $v = 22\,m/s$. Three platoons are inserted into *Lane 1*, while for *Lane 2* every 30 seconds a new car is spawned. The car positions are plot in Figure 5.13.

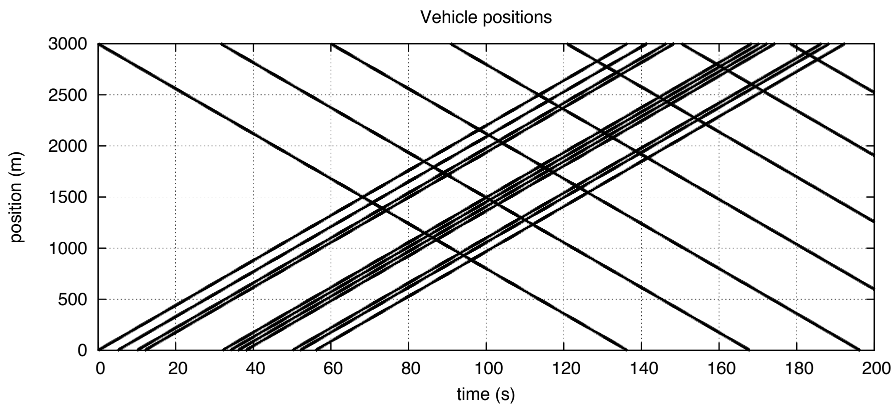

Figure 5.13: Vehicle positions for the advanced mobility model.

For this scenario a large number of simulations have been performed, each with a unique set of parameters. Goal of these simulations is to determine how the altered parameters influence the ACOS' performance. Each of the following figures showcase the influence of the *time-span* for one of the following broadcast frequencies: $1\,Hz$, $2\,Hz$, $3\,Hz$, $4\,Hz$ and $10\,Hz$. For each figure a set of 12 unique simulations were performed. This adds up to a total of 60 simulation runs with the advanced mobility model.

In Section 5.2 was chosen to focus on the vehicles A, B and C. Vehicle A has no traffic in front on its own lane. Vehicles B and C are located in the two following platoons. See page 80 for more information on why this selection was made.

Figure 5.14 through 5.18 show the simulation results for the selected broadcast frequencies. The top left graph displays the *RMS vision*, the Root Mean Square (RMS) of all measurements on the level of vision for that specific vehicle. The top right graph displays *MAX vision* which is the RMS for the 20 best measurements on the level vision for that same car. This allows to monitor the protocols' best achievements.

The bottom left graph shows Car C's road-view repository over time for a fixed life-span of $1000\,ms$. Each dot represents a detected vehicle at a certain point in time. E.g. at time $t = 80\,s$ the y-axis shows at what position on the road a car was detected, CAR C included. When analysing this graph, one can observe how the road-view's level of detail changes for the different broadcast frequencies.

And last, the bottom right graph shows the RMS number of vectors that have been broadcasted inside the PDUs, together with the maximum perceived value.

5.3.4 Influence of the broadcast Frequency

When interpreting Figure 5.14 through 5.18, it is directly noticeable that Car A's performance is not influenced by changing the broadcast frequency, nor by altering the *time-span*. This vehicle's vision is entirely limited by the VANET connection range and is not helped by exchanging PDUs with other cars. It does however functions as the 'eyes' for Car B and at times even for Car C. Although these platoons are not interconnected, occasionally information traverses through vehicles driving in the opposite lane.

With a fixed value for *time-span*, the road-view graphs for Car C give a good indication what what kind of influence the broadcast frequency has. The higher the frequency, the more detail is obtained and the farther ahead can be looked. This can also be concluded from the graphs showing the level of vision. When more messages are exchanged per time interval, the chance is bigger that available multi-hop paths will be taken advantage of, increasing the ACOS's performance.

This performance increase is very clear for the lower broadcast frequencies. But, when looking at Car C's road-view, the results for $4\,Hz$ and $10\,Hz$ seem comparable with respect to the discovery of vehicles up ahead. Since a higher broadcast frequency creates more data traffic and requires more

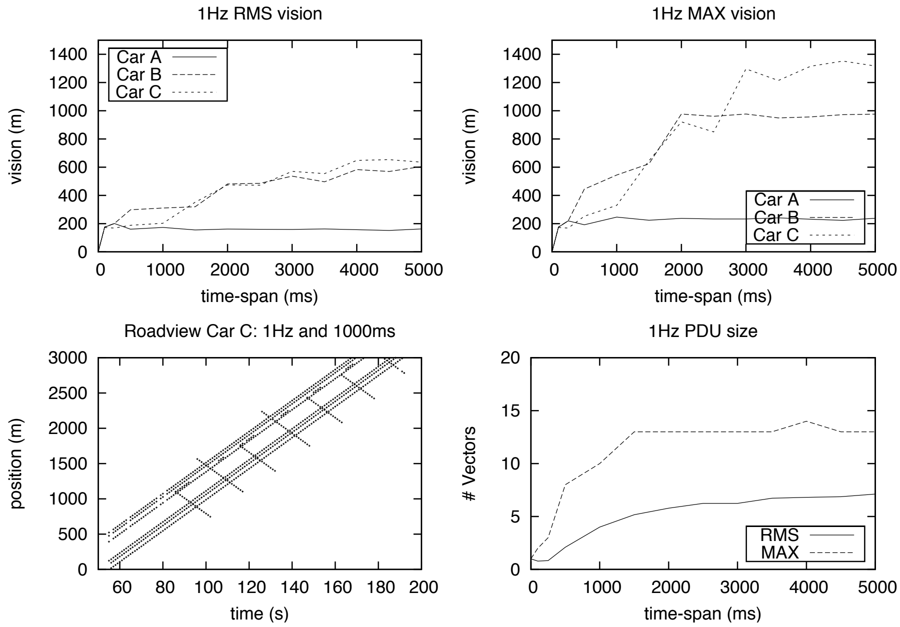

Figure 5.14: Simulation results for 1Hz.

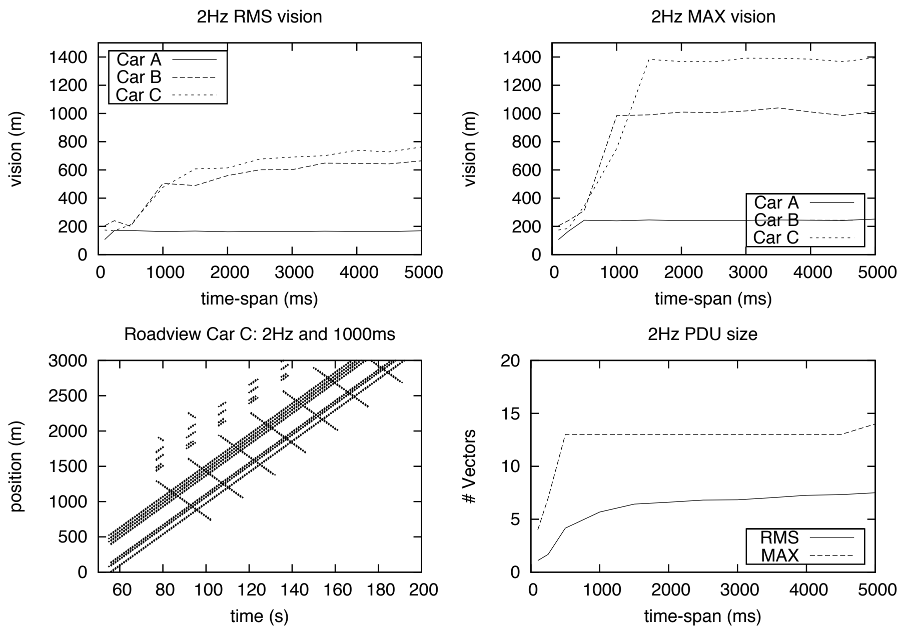

Figure 5.15: Simulation results for 2Hz.

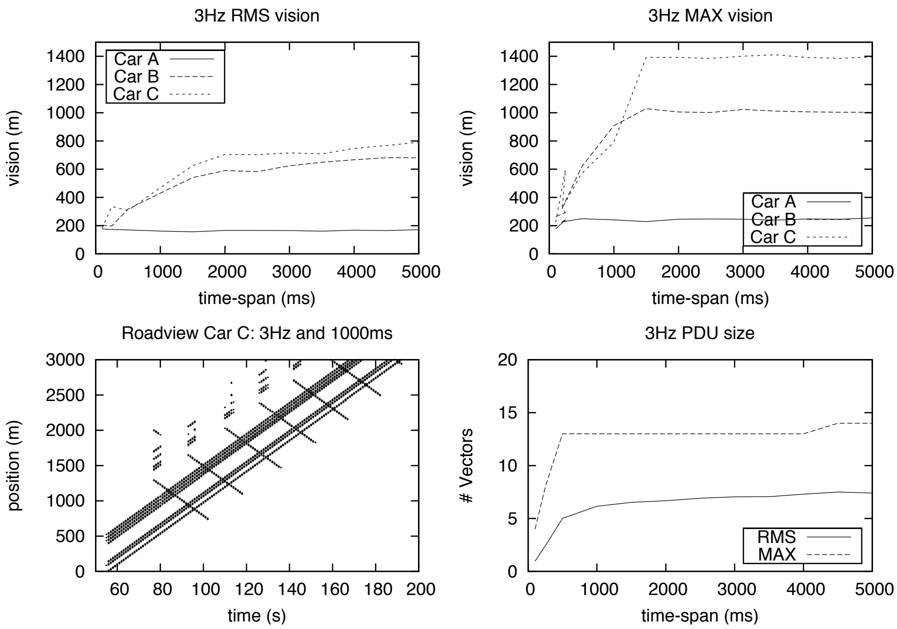

Figure 5.16: Simulation results for 3Hz.

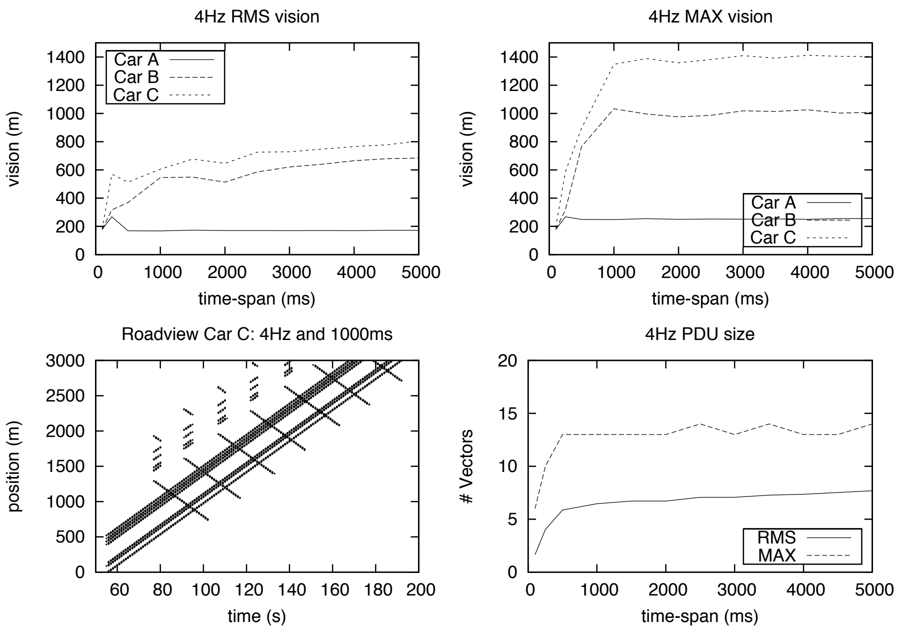

Figure 5.17: Simulation results for 4Hz.

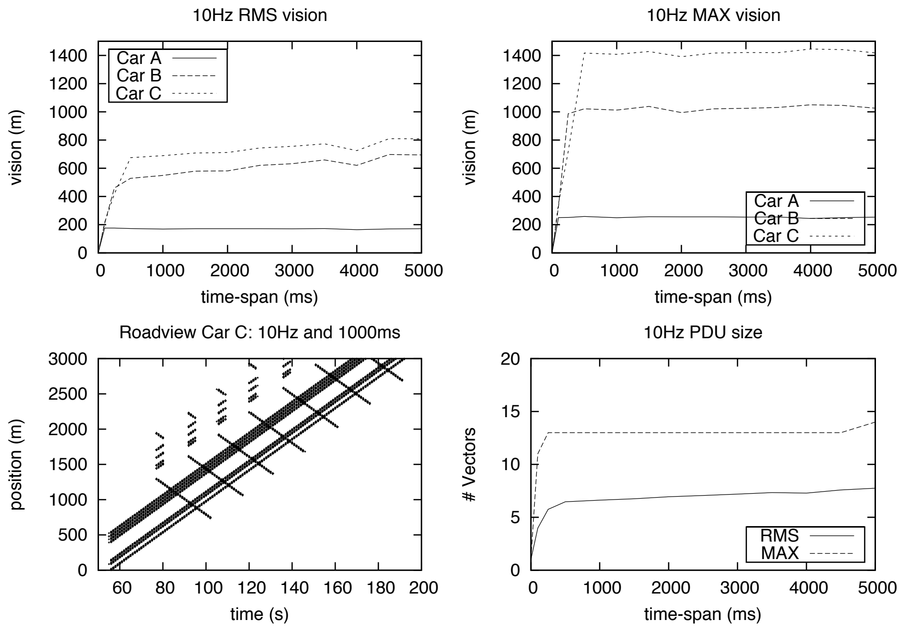

Figure 5.18: Simulation results for 10Hz

processing by the ACOS instances, it is best to use the lowest frequency that still gives a good performance figure. In this case $4\,Hz$.

5.3.5 Influence of the time-span

The influence of the *time-span* was determined for each of the selected broadcast frequencies. Setting the *time-span* to a value close to zero has a negative influence to the degree of vision. For the low broadcast frequencies an increase in *time-span* clearly improves the performance figures. Gathered data gets a higher chance to be rebroadcasted over long multi-hop paths when those become available.

In other words, the the *time-span* cancels out the negative effects of a low broadcast frequency. Besides, the carrying around of data also allows to bridge small gaps in connectivity. This can be illustrated by giving the road-view for a fixed broadcast frequency and two values for the *time-span*, as is done in Figure 5.19. The cars coming from the other side, with respect to Car C, still carry around valuable information about vehicles that were discovered some time ago.

Making the *time-span* infinitely long will results in road-view's that are capable of recovering all vehicle positions at any point in time. This would however also require an infinite number of available vectors slots in the PDU and, more importantly, will result in the deliverance of overdue vectors. The

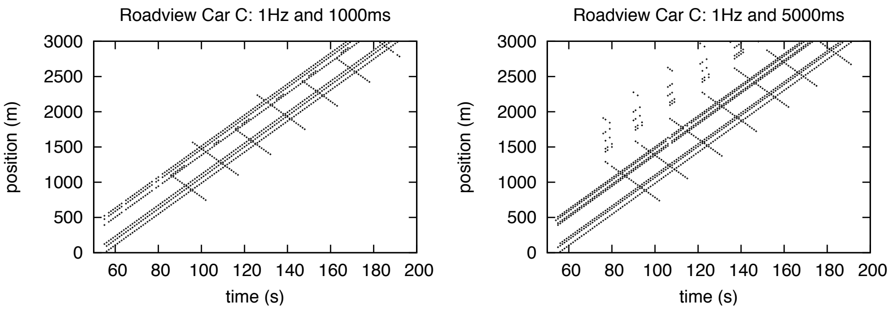

Figure 5.19: The influence of *life-span*.

longer data is saved, the less accurate it becomes. Therefore it is important to keep the *life-span* as short as possible. For the researched scenario the combination $4\,Hz/2000\,ms$ gives just as workable results as $4\,Hz/5000\,ms$, making the first mentioned the better option.

5.3.6 Influence of data extrapolation

Chapter 4 introduced a method for data extrapolation. The more remote other vehicles are situated, the smaller the chance to retrieve information from these vehicles. Once two vehicles move out of each other's range, or when the VANET repeatedly fails to deliver a message, data extrapolation injects the ACOS with assumed new positions about the vehicle that *disappeared*.

A simulation is performed to asses whether this approach is successful or not. For doing so, the advanced mobility model is applied. Figure 5.20 shows two identical simulations with data extrapolation turned on and off.

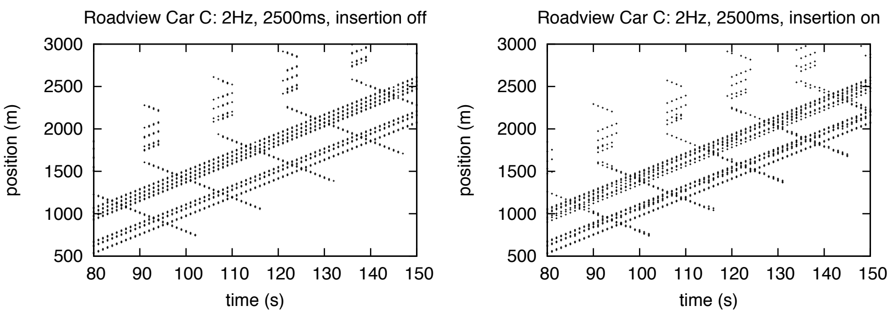

Figure 5.20: The influence of data extrapolation.

The right part of Figure 5.20 does not show an obvious increase of visibility or vehicle discovery. However, for the areas where the information density is high, some discontinuous lines can observed. This can be explained by extrapolation errors. When a possible new location is determined and this vector is broadcasted, it has a discrepancy with the original vehicle. So, when genuine information about a certain car becomes available again, it's position can jump places in the graph.

It can be concluded that data extrapolation, by the method as proposed in this thesis, does not significantly improve the ACOS' performance.

5.3.7 Conclusions

To a certain extent increasing the broadcast frequency has a positive influence on the protocol's performance. For the advanced mobility model a broadcast frequency of $4\,Hz$ seem to fulfil the requirements. As for the *life-span*, carrying around data for $2000\,ms$ seems the best choice. Take note that these parameters are chosen for this single scenario. Under different circumstances the *life-span* might have to be increased or decreased.

All the uncertainties set aside, the simulation runs so show that a relative light-weight dissemination protocol is able to provide sufficient information to re-create an image of the surrounding traffic.

Chapter 6

Evaluation

This chapter starts with comparing the simulation results with the advanced mobility model to the requirements as they were defined by Chapter 3. In addition, Section 6.2 discusses the dissemination protocol's scalability and Section 6.3 assesses its design by looking at a selection of qualitative characteristics.

6.1 Requirements fulfilment

6.1.1 Coverage range

In Chapter 5 the advanced mobility model was introduced to asses the ACOS' capabilities. For the overtaking manoeuvre three distinct vehicles were investigated in detail: vehicles A, B and C. Vehicle A had no traffic ahead that was driving on the same lane. Throughout all simulations it was observed that this particular vehicle could discover traffic at most $200\,m$ ahead. In fact, its level of vision was entirely limited to the VANET's communication range.

In contrast, vehicles B and C were helped by the information spread as provided by the dissemination protocol. In some occasions these vehicles were able to detect upcoming traffic up to $1500\,m$ ahead. This allowed the vehicles to detect a gap in the opposing traffic that could be used to perform an overtaking manoeuvre.

These performance figures clearly reveal that the information spread heavily relies on the amount of traffic and the individual positions of vehicles. Throughout the development of the ACOS, the following paradigm surfaced more and more.

- The fewer cars on the road, the higher the possibilities to overtake and the lower the probability for the ACOS to determine whether that would be safe or not.

– The more cars on the road, the smaller the possibilities to overtake and the higher the probability for the ACOS to determine that it is not safe to overtake.

Explained in simple terms, the ACOS needs cars to figure out if a driver can overtake or not. If those cars are not around, the ACOS is unable to provide a sensible advices on overtaking or not. But, it are just those circumstances where the ACOS could be of major use: when the roads are empty and one can overtake. On the contrary, the ACOS performs best when the roads are busy and overtaking is unlikely.

6.1.2 Comparison

In Chapter 3 it was concluded that for the approaching of a slower or even a stationary vehicle, a range up to $450\,m$ should be considered. For the overtaking scenario it is required that up to $900\,m$ can be bridged. When matching these numbers with the coverage ranges as experience throughout the simulations, it can be concluded that these requirements sometimes are met and sometimes not. As mentioned in the previous section, the ranges that are bridged by the system are dependent on the amount of traffic and the individual positions of vehicles. This insinuates that the system is not able to provide a reliable service at all times.

6.2 Scalability

The ACOS dissemination protocol can successfully be deployed nation-wide due to its ad-hoc approach and the locality of its operations. In other words, the ACOS satisfies the requirement to operate at least nation-wide; it could even be deployed world-wide.

Although the size of the system's deployment is not limited, the density of vehicles in the system is. As given by Equation 4.3 on page 64, each PDU can carry information about at most 135 vehicles. When more fields are added to the PDU, e.g. for security purposes, this number will have to be reduced considerably. Figure 6.1 gives a possible traffic environment where this limitation might lead to malfunctions. Just a small number of hops will result in a large number vehicles to be be tracked by each individual vehicle.

This problem could be solved, or at least be reduced, by selecting a very low value for the *life-span* parameter. By doing so, only a limited number of nodes will be reached outside the immediate broadcast range. A better and more elegant solution would be the implementation of an intelligent dissemination protocol. Such a protocol should have the ability to evaluate gathered information on its usefulness and only re-broadcast the most valuable data. Also, it should be able to adjust the *life-span* and

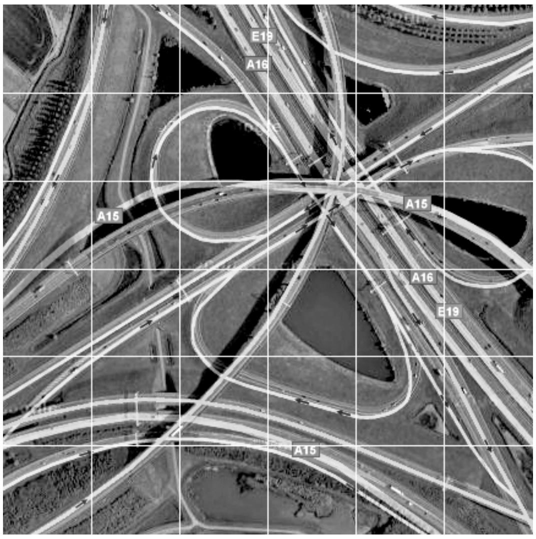

Figure 6.1: High-capacity interchange near Barendrecht, The Netherlands.

broadcast frequency to its environment. A traffic situation like depicted in Figure 6.1 asks for different broadcast behaviour compared to country road.

6.3 Protocol characteristics

Previously, the following qualitative characteristics were introduced: *Loop-Freedom*, *Distributed Operation*, *Path strategy* and *Memorisation*[1]. The following list discusses into what extent the ACOS dissemination protocol compares to these characteristics.

Loop-Freedom - The ACOS dissemination protocol is not free of loops with respect to data chunks. Information generated by a certain *Node A* can - and most certainly will - be returned to this very same *Node A*. Such information paths starting and ending at *Node A* can be composed from both single and multiple hops.

However, each broadcasted packet is by definition unique as it always encapsulates up-to-date information about its originator. Packets, containing information about several nodes, are never ignorantly rebroadcasted as they come.

Distributed Operation - Each ACOS instance has detailed knowledge on the behaviour of surrounding and remote nodes. This information is however not (yet) put into use for other networking purposes.

[1] See page 15 for a description for each of the characteristics.

Path strategy - The protocol's behaviour can be described as *flooding*, both generated and received information is forwarded to all other nodes within range. However, the ACOS dissemination protocol is distinct compared to classic flooding mechanisms since it does not simply receive and forward each packet. Instead, information is continuously gathered, evaluated and summarised to be periodically broadcasted to surrounding nodes. This approach prevents the system from a so-called *broadcast storm*.

Memorisation - Since the ACOS simply performs a periodic broadcast, it is not required to memorise networking paths for any other topology related information.

The ACOS dissemination protocol is rather simple, each node periodically shares its gathered data with other nodes within reach. Its operation does not require any knowledge about the network's topology, each packet always contains valuable new information and a *broadcast storm* is by design impossible. Hence, the protocol can be characterised as being effective and robust.

Chapter 7

Conclusions & Recommendations

This chapter wraps up the research as it was performed for my thesis. First, Section 7.1 gives short and concise answers to the research questions as they were introduced in Chapter 1. Next, in Section 7.2, some ACOS related issues are briefly discussed. And, finally, Section 7.3 lists several recommendations and possible future investigations.

7.1 Conclusions

Before answering the actual research questions, a short overview is given on how these questions were tackled. First, a state-of-the-art on VANETs was provided in Chapter 2. This allowed to both get familiar with the subject and to select the appropriate communication technology for the overtaking system.

Second, a mathematical model was developed for both the approaching of a slower vehicle and the overtaking manoeuvre. This allowed to determine what kind of information has to be exchanged among the vehicles and what communication distanced have to bridged by the system.

Third, a dissemination protocol was proposed to be used for the ACOS. And fourth, a simulator was developed to analyse the performance of this dissemination protocol. For doing so, it was also required to get more insight into the IEEE 802.11p standard's networking performances.

7.1.1 Selection of Vehicle Ad-Hoc Network

What Vehicle Ad-Hoc Network is most suitable for an Advanced Co-operative Overtaking System?

Because the USA aims to incorporate the WAVE protocol stack and the European C2C-CC is currently developing a standard based the same IEEE guidelines, it is to be expected that upcoming VANETs will rely on the CSMA/CA MAC approach. For both continents a 10 Mhz band has already been assigned for traffic purposes, this band could be used for overtaking assistance. Therefore, it is most suitable to select the IEEE 802.11p standard as the underlying technology for the ACOS.

What are this technology's current issues?

The IEEE 802.11p standard is ratified in 2010 and hence no radio equipment is currently available, nor performance figures based on live measurements. This makes all research based on VANET technology, this thesis included, rather speculative. Furthermore, the technology suffers the *hidden-node* problem, has to cope with a vast range of working environments and and rapid topology changes. The quality of communication can possibly be much lower as anticipated upon.

7.1.2 Definition of service requirements for an Advanced Co-operative Overtake System

What distances have to be covered by means of wireless communications?

The required distances to be covered are dependent on a selection of variable parameters, with velocity and the overtaking acceleration being the most influential ones. For the approaching of a slower or even a stationary vehicle, a range up to 450 m should be considered. For the overtaking scenario it is required that up to 900 m can be bridged.

7.1.3 Feasibility of an Advanced Co-operative System feasible

Is it possible to bridge the distances that results from question 2.a?

The simulations revealed that the information spread heavily relies on the amount of traffic and the individual positions of vehicles. At times the required distanced can be bridged, at other times this is impossible. This means that it will not always be possible to assist the driver with the overtaking procedure.

Could such a system be applied to trigger overtaking manoeuvres?

No, the system can not be applied to trigger overtaking manoeuvres. The ACOS is not at all times capable to assure the driver's safety. The required distances can not always be bridged and there is always a possibility that car vectors get lost. The overtaking manoeuvre brings the driver, and other traffic attendants, in a fragile situation where total safety cannot be assured by the system.

Could such a system contribute to a safer traffic environment?

Yes, the system is capable to prevent hazardous situations. If a driver ignites an overtaking manoeuvre and the ACOS detects possible danger, then the driver can be provided a warning. Hence, the system can contribute to a reduction of traffic accidents.

7.2 Discussion

As mentioned before, the IEEE 802.11p standard has been ratified in 2010, but no largely deployed implementations are available. Hence, all performance figures can be considered to be speculative. By the time performance figures on real-life deployment of this technology become available, it will become much easier to develop and asses a dissemination protocol as proposed by this thesis.

The duration of an overtaking manoeuvre depends on a large set of variables. Some of these variables are unknown prior to the manoeuvre itself, introducing uncertainty to the system. It is inevitable that assumptions have to be made on e.g. the overtaking acceleration or target velocity. For this work was attempted to generalise the driver's behaviour is much as possible. This creates a danger as every driver is unique and its safety is at stake.

The required distances to be bridged by the VANET, as defined in Chapter 3, seem to be on the very safe side. The ACOS would be able to meet loosened up requirements - thus shorter distances to be bridged - with a higher probability. Therefore it could be interesting to re-evaluate this approach for smaller safety distances.

On the other hand, even if VANET technology allowed to communicate over distances up to $1\,km$, there always remains the risk for communication fails. Or worse, that a vehicle's ACOS is malfunctioning. Concluding, even for improved communication distances it would still not be possible to actively trigger people to perform an overtaking manoeuvre. People's lives should never be put at stake.

For the ACOS to be deployed, it is required that every vehicle attending traffic is equipped with a working system. This requirement is very demanding and needs full international government regulations to be realised.

7.3 Recommendations

This section outlines several related topics that can be researched to improve the functioning of such an overtaking system as proposed in this work. Especially active knowledge about road topology, as discussed in Section 7.3.5, seems a very attractive improvement. Nowadays many cars are already equipped with advanced navigation system.

7.3.1 Intelligent rule-set

In Chapter 5 the influence of the *life-span* and broadcast frequency was determined. In sparse populated areas a higher performance can be achieved by increasing the *life-span*, it allows to detect remote vehicles. However, in dense areas this could lead to an overflow of vector information. Therefore it can be researched under what circumstances what life-span and broadcast frequency settings give the best performance results. This could eventually lead to an intelligent rule-set.

7.3.2 Directional antennas

The use of directional antennas allows to more specifically target the forwarding and receiving of messages. More importantly, it allows to bundle its power into a smaller beam and thus reach vehicles further ahead compared to an omnidirectional antenna. A design choice could be to only forward information into the driving direction. On the one hand this could allow to reach more distant vehicles, on the other hand it might introduce blind spots in the road vision. The latter happens when vehicles are moving on curved road sections. Concluding, research can be performed to asses whether the use of directional antennas is feasible or not.

7.3.3 Repeating nodes

This work adopted the approach where communication only happens in a vehicle-to-vehcicle fashion. It can be researched into what extent VANET/A-COS performances can be boosted by installing stationary repeating nodes aside the road. Such nodes can function as intermediate hops to increase the probability that information will be forwarded over large distances. The effect can be measured by researching what happens if every e.g. 1 km information is repeated by roadside equipment. This method could especially be beneficial on roads located in remote areas.

7.3.4 Vector aggregation

As earlier explained in Section 4.9, vector aggregation provides a method to effectively reduce the amount of data to be transmitted. Unfortunately it also introduces a higher level of complexity to the system. Examples of issues are how to determine the direction and speed of the groups of cars, and how to handle possible conjunction these groups. The broadcasting

PDU as proposed in thesis is already designed with vector aggregation in mind. See page 66 for more information on this topic.

7.3.5 Road maps

Knowledge about road topology could highly improve the ACOS' effectiveness and accuracy on two fields of interest. First, it allows to detect hazardous situations to a greater extent. Overtaking can automatically be discouraged in complex infrastructures and vehicles can be detected that are approaching from connected roads. Second, a gain can be achieved on the networking level by only forwarding information to relevant vehicles. This could for example allow a larger *life-spane*, increasing the road view. Summarasing, knowledge about the environment allows the ACOS to make more intelligent decisions and better target information forwarding.

7.3.6 Multipurpose dissemination protocol

Many VANET applications can be thought of that could benefit from the road-view as created by the ACOS. Besides safety applications, one can also think of traffic flow control or traffic-jam detection. Such applications might require a slightly different set of information to be exchanged and likely perform better with other broadcast settings. Therefore it seems feasible to develop a multipurpose dissemination protocol that can be put to use for a broad range of applications.

Appendix A

ACOS Simulation Tool

This chapter gives an informal overview of the simulator that specifically was developed for this research. First Section A.1 gives a brief insight to its implementation, then Section A.2 explains its functioning by describing several screen shots and finally Section A.3 discusses a minor issue.

A.1 Implementation

The simulator was implemented in the Java programming language by applying the Model-View-Controller (MVC) design pattern. It is constructed as depicted in the pseudo UML diagram below.

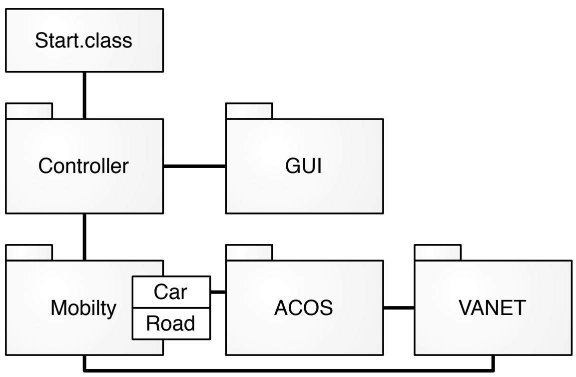

Figure A.1: Pseudo UML diagram outlining the simulator's design.

Initialising the simulator is done by running *Start* that creates a controller instance. Next, this controller creates the graphical user interface *GUI*. The *GUI* allows the user to set a range of simulation parameters and displays the simulation progress and results; see Section A.2 for some screenshots

The user is allowed to start a simulation when all parameters are set correctly. Now the controller uses the *Mobility* package to create a simulating environment. A road is modelled by creating two distinct lanes with opposite driving directions. At the starting point of each lane new cars are inserted every certain time interval. Every car hosts an *ACOS* instance that manages the dissemination protocol. Each of these *ACOS* instances have access to the 802.11p MAC through the *VANET* package. Every $8\,\mu s$ the cars are set to their new positions and is wireless communication handled. This is repeated until the end of the simulation time has been reached.

After the simulation is finished, the *GUI* presents the user with the paths that all cars have traversed. Also, for every car a logbook can be accessed that graphically displays all information that was received from other the vehicles. Other information, such as back-off times, the degree of vision and the number of packet collisions are written to files.

A.2 Screenshots

This section contains a selection of screenshots to present the simulator's functionality. Figure A.2 shows the options under the mobility tab. Here the length of the road can be defined, just like the velocities of the cars and their arrivals at both sides of the road.

Figure A.3 shows the VANET options. The bandwidth influences how long it takes for a PDU to be sent, the maximum range defines the power of the transmitter. In addition it is also possible to define several MAC parameters. Throughout this research the VANET parameters have always been fixed to that values as shown in the Figure A.2.

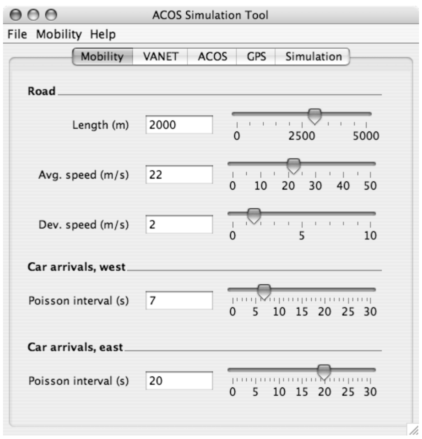

Figure A.2: Mobility settings.

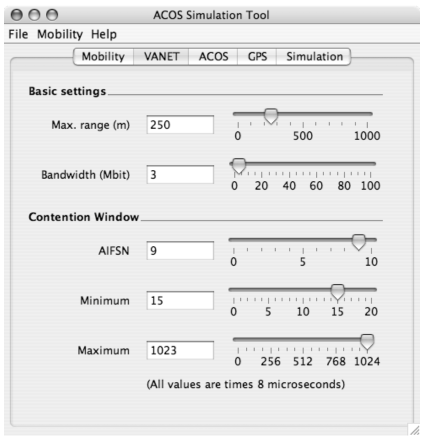

Figure A.3: VANET settings.

Figure A.4 shows the ACOS dissemination settings. The broadcast frequency can be altered by setting the interval in milliseconds between the transmission each PDUs. Time frame denotes the *life-span* of the created information. Linear insertion can be toggled on and off by a radio button.

Figure A.5 show how GPS behaviour can be altered. Appendix B goes into more detail about this specific issue.

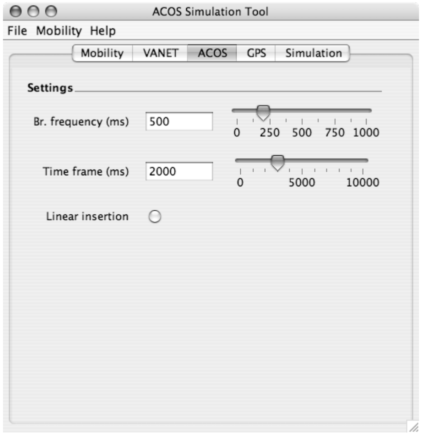

Figure A.4: ACOS settings.

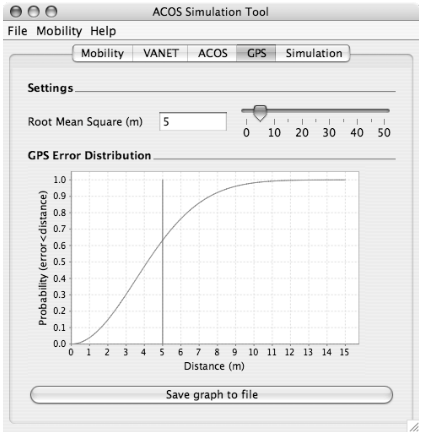

Figure A.5: GPS settings.

Figure A.6 shows that the simulation run time can be altered. The ability to alter the step size is a legacy function, steps are always fixed to $8\mu s$. Section A.3 explains this issue into more detail.

The feedback field show the progress of the simulation. When the tool is finished simulating, it will be made possible to select a car and display its *road-view*. The latter is displayed in Figure A.7.

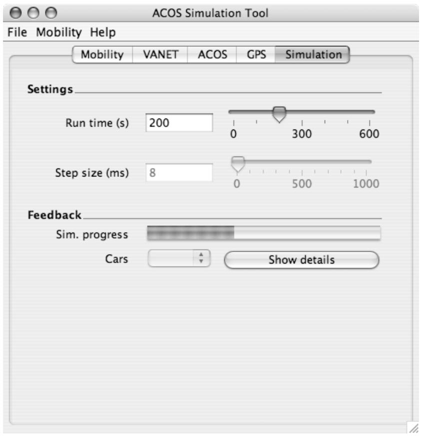

Figure A.6: Simulation settings 1.

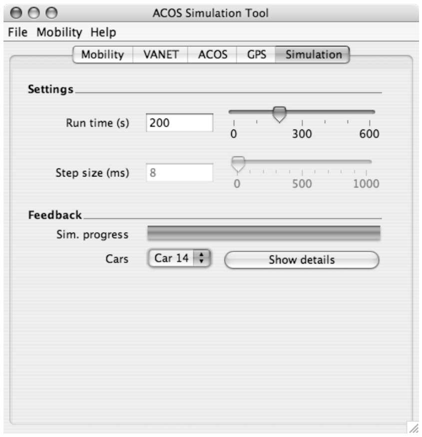

Figure A.7: Simulation settings 2.

The window from Figure A.8 shows all cars from the simulation run, it will be automatically generated when the simulation is finished. The horizontal axis show the running time and the horizontal axis the length of the road. Each car is displayed with a unique colour. It is also possible to zoom in on the graph.

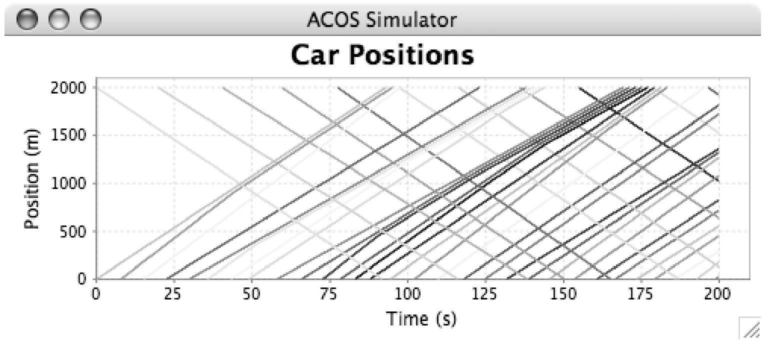

Figure A.8: Graph showing all car positions throughout the simulation.

Figure A.9 shows all received information for - in this instance - car number 14. Such a graph can be obtain for each individual car that was creating during the simulation. Every dot represents a vector that was received and then stored in this car's *road-view*. For this figure was zoomed in to a smaller period of time within the simulation.

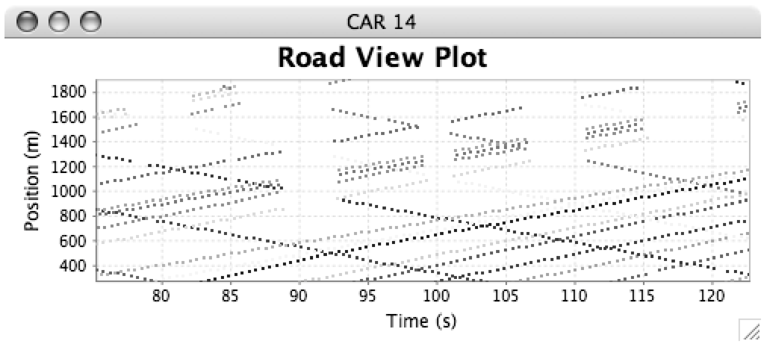

Figure A.9: Graph window presenting the generated *road-view.*

A.3 Discussion

As throughout the simulation runs no packet collision was experienced, the simulator could have been implemented much simpler by incrementing the time with larger steps compared to the 8 μs that is applied now. By applying this method, message exchange can be performed instantly, making the MAC layer unnecessary.

In a first stage the simulator was actually implemented with this approach, but then it was not yet known that this approach could have been sufficient for this research.

Appendix B

Global Position System

Section B.1 briefly presents how the Global Positioning System (GPS) operates, followed by Section B.2 where the GPS error distribution is presented to the reader. Fluctuations in GPS accuracy directly influence the ACOS QoS since the overtaking system relies on GPS data for determining vehicle positions. For this reason the author has chosen to briefly look into this matter.

B.1 Introduction

Currently, the GPS is the only fully operational navigation system. It is at all times composed from at least 24 satellites, all located in the earth's medium orbit area. Each of these satellites continuously transmits microwave signals that allow a GPS receiver to solve the variables x, y, z and t, the receiver's position and local time respectively. These values are then converted into more conventional notations, such as latitude/longitude or the location on a given map. A minimum of four GPS signals is required for an accurate result. The more satellites within reach, the more precise the determined position will be.

GPS was developed by the United States Department of Defence and is still maintained by the USA. Examples of similar systems are the Russian GLONASS (which is currently being restored and modernised), the Euopean Galileo project (currently being deployed) and the Indian IRNSS (still in developed). All these initiatives are motivated by being independent from the USA for navigational purposes.

B.2 GPS Error Distribution

The GPS signal tends to be relatively weak, therefore the receiver can be desensitised by other sources of electromagnetic radiation. These sources can be both natural or artificial. Solar flares is such a natural phenomenon that potentially degrades GPS reception. It can affect all signal reception on the entire half of the earth facing the sun. Another example is the occurrence of geomagnetic storms.

Noise from Electromagnetic Interference (EMI) also influences the GPS reception. EMI can result from e.g. cell phone signals or other means of wireless communication. In addition, metallic features in windshields can result in a Faraday cage, affecting the signal's quality inside the vehicle.

As stated before, at least four different GPS signals are required to determine the receiver's position. These GPS signals can be slightly altered or even be totally jammed due to interference or environmental characteristics. Hence, numerous techniques are developed to improve or repair the perceived GPS information. Typically a receiver's quality is characterised by these methods, together with antenna features.

Every type of GPS receiver has a unique accuracy given by its Root Mean Square (RMS) error in meters[1]. Equation (B.1) gives the GPS error distribution as function of the receiver's RMS value, it is taken from [69]. The accuracy of a commercial GPS receiver is typically given by $RMS = 5.5$

$$P(Error < Distance) \quad = \quad 1 - e^{-(RMS - Distance)^2} \tag{B.1}$$

This equation is visualised by Figure B.1, showing the error distribution for three different RMS values.

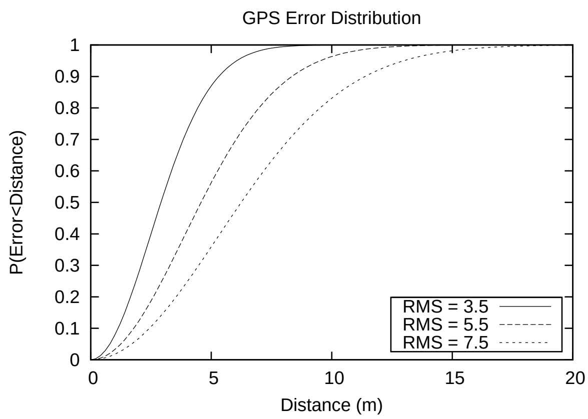

Figure B.1: GPS error distribution.

It can be concluded that when the receiver's accuracy drops, for whatever reason, the perceived vehicle position can significantly be altered. This indicates that the ACOS should incorporate a GPS safety margin.

[1] The GPS receiver's specification should state this information.

Detailed information about the GPS can be found in the book [70]. Also, some interesting measurements on GPS accuracy are pointed out in [71].

Appendix C

ASN.1 Notation

The Abstract Syntax Notation One (ASN.1) is a formal language developed by the International Telecommunication Union (ITU). It provides a set of formal rules for describing the structure of objects for telecommunications and computer networking. The notation is independent of machine-specific encoding techniques and is a precise, formal notation that removes ambiguities. What follows is the ASN.1 notation for the PDU as described in Chapter 4.

```
DP.ID ::= INTEGER ( 0..255 )
DP.Tst ::= INTEGER ( 0..16777216 )

T.Tst ::= INTEGER ( 0..16777216 )
T.Pos ::= OCTET STRING ( SIZE(8) )
T.Dir ::= INTEGER ( 0..255 )
T.Spd ::= INTEGER ( 0..255 )
T.Acc ::= INTEGER ( 0..255 )
T.Dia ::= INTEGER ( 0..255 )

DP.Vec ::= SEQUENCE {
  T.Tst INTEGER,
  T.Pos OCTET STRING,
  T.Dir INTEGER,
  T.Spd INTEGER,
  T.Acc INTEGER,
  T.Dia INTEGER
}

V.Tst ::= INTEGER ( 0..16777216 )
V.Pos ::= OCTET STRING ( SIZE(8) )
V.Dir ::= INTEGER ( 0..255 )
V.Spd ::= INTEGER ( 0..255 )
```

```
V.Dia ::= INTEGER ( 0..255 )
V.NuV ::= INTEGER ( 0..255 )
V.IDs ::=
V.FLG ::= BIT STRING ( SIZE(8) )

RV.Vec ::= SEQUENCE {
  V.Tst INTEGER,
  V.Pos OCTET STRING,
  V.Dir INTEGER,
  V.Spd INTEGER,
  V.Dia INTEGER,
  V.NuV INTEGER,
  V.IDs  ,
  V.FLG BIT STRING
}

RV.Len ::= INTEGER ( 0..255 )
RV.Vectors ::= SEQUENCE OF RV.Vec

DP.RoadView ::= SEQUENCE {
  RV.Len INTEGER,
  RV.Vectors
}

PDU ::= SEQUENCE {
  DP.ID  ,
  DP.TST INTEGER,
  DP.Vec SEQUENCE,
  DP.RoadView SEQUENCE
}
```

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