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Methods to Improve V2V Communications in Platoons of Heavy Duty Vehicles

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To Vilma, Sigge and Hedda

Abstract

In the coming years V2V communications will probably be mandated and vehicle OEMs strive to find business opportunities to finance its investments in V2V communications technology. For heavy vehicles, platooning can be this business opportunity, with the motivation for the fleet owners that platooning can decrease the fuel consumption by up to 15 % when driving in platoons. However, challenges still exists with respect to the quality and reliability of the V2V communications, which is essential in order to enable platooning in a safe way.

In this thesis, two proposals of improving the quality and reliability of V2V communications in a platooning scenario are presented. The first proposal is the Curvature Based Antenna Selection Method that utilize the curvature of the road in order to estimate which antenna have the highest probability of having line of sight conditions, hence highest probability of successful communication. The method assumes a platoon of heavy vehicles with one antenna mounted in each rear view mirror. It also assumes that the leading vehicle can estimate the yaw rate of the platoon in order to determine if it is turning or not. The second proposal include two message forwarding algorithms, the Reachability Matrix forwarding algorithm and the Data Age Dependent forwarding algorithm. Both algorithms utilize information on the preceding communication capability in order to estimate which node to choose as forwarding candidate. The Reachability Matrix Algorithm puts its focus on keeping the overhead low, while at the same time improve the information up-to-dateness. The Data Age Dependent algorithm instead puts its main focus on performance with respect to improving the information up-to-dateness, with the cost of higher overhead compared to the Reachability Matrix algorithm.

Both proposals show potential of improving the quality of the V2V communication in a platooning scenario. The first proposal, the antenna selection method, is able to maintain a Data Age deadline of 150 ms approximately twice as often as when selecting transmission antenna in a round robin fashion. For the second proposal, the Reachability Matrix Algorithm reduces the miss of a 0.2 s Data Age deadline in the communication between the first and the fourth vehicle in a platoon from 18 % to 11 %, while only increasing the number of

sent messages from 40 to 48.5 per second compared to when only broadcast is used. The Data Age Dependent algorithm shows even better performance with respect to reducing the missing of the 0.2 s Data Age deadline, i.e., with a reduction from 18 % to 5 %.

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Marcus Larsson
Gothenburg, December 2015

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List of Publications

The thesis summarizes the following papers

A. M. Larsson, M. Jonsson, K. Karlsson, C. Bergenhem, and T. Larsson, "Curvature based antenna selection method evaluated using the data age metric and V2V measurements," in *Proceedings of IEEE ICC 2015 - Workshop on Dependable Vehicular Communications*, London, United Kingdom, June 2015.

   Contribution: I have, under supervision of M. Jonsson, iteratively developed the method of choosing transmission antenna. I have, in collaboration with K. Karlsson, developed the MATLAB analysis tool for evaluation of the method. I have also participated in the planning and execution of the measurement campaign from which we collected V2V communications data.

B. M. Larsson, F. Warg, K. Karlsson, and M. Jonsson, "Evaluation of a low-overhead forwarding algorithm for platooning," in *Proceedings of IEEE International Conference on Vehicular Electronics and Safety (ICVES)*, Yokohama, Japan, November 2015.

   Contribution: The basic ideas of the algorithm was designed by me under supervision of M. Jonsson. The simulation environment was designed and implemented by K. Karlsson, F. Warg and me. The algorithm was implemented by F. Warg and me. I performed the simulations and the analysis of the results.

C. M. Larsson, M. Jonsson, F. Warg, and K. Karlsson, "A data age dependent broadcast forwarding algorithm for reliable platooning applications," Submitted to journal for reviewing.

   Contribution: I have, under supervision of M. Jonsson designed the basic ideas behind the algorithm. I implemented the algorithm in the simulation environment and performed the simulations and the analysis of the result.

The simulation environment was designed and implemented by K. Karlsson, F. Warg and me.

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Abbreviations

ATRI	American Transportation Research Institute
BSS	Basic Service Set
CAM	Cooperative Awareness Message
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
D2D	Device to Device
DOT	Department of Transportation
EEBL	Emergency Electronic Brake Light
ETSI	European Telecommunications Standards Institute
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation System
LOS	Line of Sight
MAC	Medium Access Control
OEM	Original Equipments Manufacturer
OSI	Open Systems Interconnection
PER	Packer Error Rate
PHY	PHYsical layer of the OSI model
SARTRE	SAfe Road TRains for the Environment
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle

Chapter 1
Introduction

1.1 Motivation

In recent years the emerging field of intelligent transportation systems (ITS) has gained a lot of attention in the research community [1, 2, 3]. Controlling traffic lights at a macro level, intelligent pedestrian crossing and platooning are applications that all fits in the ITS eco system. One of the main enabling technologies for ITS is wireless communication, which enables cooperative applications such as platooning [4] mentioned above. In 2010, IEEE released the IEEE 802.11p standard for wireless access in vehicular environments [5]. This standard opens the possibility to implement cooperative functionality in a vehicular context. The emphasis in this thesis is on vehicle to vehicle (V2V) communication in a platooning scenario for heavy duty vehicles, were the vehicles drive in a highly automated fashion with short inter vehicle distance in order to save fuel. The fuel is saved as a consequence of the reduced air drag, caused by the short distance [6].

In order for platooning to become a common application, a few main technologies need to be improved. First, it is essential that the vehicles can sense its surroundings. Sensing technology is rapidly enhancing and the development of radar and vision systems makes it possible for the vehicles already today to have a fairly good understanding of what objects are present in the vicinity. Second, reliable wireless V2V communication need to be established. The communication is needed in order to enable feed forward of important control input, e.g., intended acceleration and deceleration. The communication is important if a short inter vehicle distance shall be kept in a safe way. Third, control strategies need to be developed in order to keep a short inter vehicle distance and at the same time, e.g., keeping the level of driver comfort at an acceptable level.

The focus of this thesis is on the communication part were potential challenges can be foreseen for the V2V communication for heavy duty vehicles due to the geometry of these vehicles. The geometry of heavy duty vehicles makes it impossible to position one single antenna that will have line of sight (LOS) 360° around the vehicle. Moreover, IEEE 802.11p based V2V communication utilizes a carrier frequency of 5.9 GHz that is sensitive to LOS conditions, e.g., blockage and shadowing, with a rapidly decreasing performance when non-LOS conditions are present [7, 8]. Measures need to be taken in order to mitigate this loss in performance in order to have reliable wireless V2V communication. The aim of this thesis is to present approaches of mitigating the LOS problem in a platooning scenario for heavy duty vehicles.

1.2 Problem Formulation

The combination of the relatively high carrier frequency, 5.9 GHz, and the size and geometry of a heavy duty vehicle introduces problems with respect to V2V communication. My main research goal is to *improve the quality of V2V communications in a platooning scenario for heavy duty vehicles.* In order to achieve an improvement, two approaches are tried. First, I investigate the possibility of selecting transmission antenna in order to increase the probability of having LOS conditions, hence having higher probability of successful transmissions. Second, I evaluate how forwarding algorithms can increase the information up-to-dateness in every vehicle in the platoon. To evaluate these approaches the following two research questions have been elicited:

- How can the wireless transmission blockage, caused by the geometry of heavy duty trucks, be mitigated in a platooning scenario and how can it be assessed?
- How can the overall age of the information in a platooning scenario be improved?

1.3 Methodology

The underlying problems that lead to the problem formulation in Section 1.2 have been identified by a study of the state of the art literature in the area of V2V communication. With the problem formulation at hand a field measurement was planned and executed in order to collect real world data for further analysis. Methods and algorithms to solve the stated problems were iteratively designed and implemented in a simulation environment for evaluation. The simulation environment was designed in such a way that data from the real world V2V communication measurements was well suited to be used as a "channel model".

1.4 Contributions

The contributions of this thesis mainly consist of three parts.

First, a transmission antenna selection method has been developed and implemented for evaluation in a simulation environment. The analysis of the simulation results show that if the transmission antenna can be selected according to the yaw rate of the platoon then the V2V communication performance is increased.

Second, two forwarding algorithms that utilize the communication link information to choose forwarding node have been developed and evaluated in a simulation environment. The main approach for the first algorithm, the Reachability Matrix Algorithm, is to achieve a better performance than broadcast and at the same time not utilize unnecessary overhead. The second forwarding algorithm, the Data Age Dependent Forwarding Algorithm, has a higher focus on Data Age performance than the Reachability Matrix Algorithm and achieves better performance with respect to keeping the Data Age at a low level but consumes more overhead.

Third, the V2V communications measurements that has been performed on public highway using four heavy duty trucks and ETSI ITS-G5 compatible radio nodes, is a small but important contribution. These measurements has been important in order to be able to evaluate the above mentioned method and algorithms. During the measurements, two different antenna positions where evaluated. Both the rear view mirrors and the upper wind deflectors were used as mounting points for the antennas. The collected data from the measurements was used to feed the simulators that were used to evaluate the method and algorithms.

The contributions are listed below with respect to which paper they correspond to, except for the measurements that are part of all three papers.

- A simple antenna selection method utilizing road curvature to estimate the probability of having LOS conditions, hence also having higher probability of successful communication **[Paper A]**.
- A low overhead forwarding algorithm that improves the overall data age. The algorithm utilizes low resolution link information, i.e., a binary link quality indicator, in a compact manner to select the forwarding node **[Paper B]**.
- A high performance forwarding algorithm that uses high resolution link information, i.e., a link quality indicator that utilizes at least three bits, to choose forwarding node in order to keep the overall data age low **[Paper C]**. This algorithm results in better overall data age values, but utilizes higher messaging overhead than the algorithm suggested in **[Paper B]**.

1.5 Organization of Thesis

The rest of the thesis is organized as follows. Background material is presented in chapter 2. Chapter 3 summarizes the appended papers. In Chapter 4 a discussion is given, while the thesis is closed in Chapter 5 where the conclusions and future work are given.

Chapter 2
Background

2.1 Intelligent Transportation Systems

Intelligent transportation systems is an area of research that aims at increasing safety, traffic throughput and convenience while at the same time decreasing the environmental impact with respect to transportation. One definition of ITS is the one from the U.S Department of Transportation (DOT): "*the application of advanced information and communications technology to surface transportation in order to achieve enhanced safety and mobility while reducing the environmental impact of transportation.*" [9]. This definition implies that a vast variety of technologies are needed in order to enable ITS applications. It is foreseen that a continuance of the development of sensors is necessary in order to increase the local awareness in the different ITS systems. Also the sensor information need to be handled in an intelligent way, e.g., using sensor fusion in order to extract as much information as possible from the sensors. Many sensors today have the precision needed for, e.g., autonomous driving, but the cost need to reach an acceptable level for mass market production. Of course much work need to be done with respect to V2V and V2I communications in order to have safe, secure and reliable communication, more on this in Section 2.3.

ITS applications range from, e.g., pedestrian crossing warning systems to autonomous and cooperative vehicles [10, 11, 12]. These examples all aim at increasing the safety of the road users, both unprotected pedestrians and protected road users in vehicles. Self driving cars is an example where safety and convenience is of importance, but also issues like user experience and acceptance need to be evaluated thoroughly in order for ITS systems like this to reach mass market. Cooperative vehicles need to utilize much, perhaps all, of the technology in the autonomous vehicles, but they also need to be able to communicate in order to facilitate a higher level of awareness. Electronic Emergency Brake Lights (EEBL) is an example of a cooperative function that increases the safety by the use of communication [13]. The awareness of the following vehicles is enhanced by having the braking vehicle not only turning on its rear brake lights but also transmitting a V2V signal that warns the traffic behind.

2.2 Platooning

Platooning is a distributed application that controls vehicles to drive with short inter vehicle distance, having the main collaborative objective of saving fuel. Several variates of platooning exist in the literature, e.g., in the SARTRE project [14] platooning is defined as having a first vehicle, driven in a manual fashion by a trained professional driver, to lead a number of following vehicles and utilize V2V communication in order to transmit its intentions to the following vehicles. The following vehicles are controlled in an automatic fashion in both lateral and longitudinal direction using local sensors and the V2V information from preceding vehicles as input to its controllers.

The literature presents two main reasons to drive in platoons. The PATH [15] project argues that if vehicles drive in platoons the road utilization will be increased, hence lowering traffic congestion and increasing the throughput. According to the American Transportation Research Institute (ATRI) [16] the fuel cost for a long haulage fleet operator is approximately 40 % of the total operating costs. In Japan, the Energy ITS project [17] developed a four vehicle truck platooning application and implemented this and performed fuel saving measurements on a test track. When the trucks were driving in a platoon with 4.7 meters inter vehicle distance approximately 15 % fuel was saved. The SARTRE project [14] implemented and tested its version of a platooning application. Evaluation on test track showed that if the inter vehicle distance can be kept at approximately 5 meters the following heavy duty trucks can save up to 16 % fuel. They also show that the leading vehicle saves approximately 5 % fuel [18].

2.3 Vehicle to Vehicle Communications

In order to enable cooperative ITS applications like platooning, V2V communication is essential. A prerequisite to enable communication is a common understanding of in which way the communications are to be performed. For this reason, standardization organizations like IEEE and the European ETSI have created standards for this. IEEE released the IEEE 802.11p standard [5] covering the MAC and PHY layers, in 2010. This standard is based on the commonly known IEEE 802.11 standard, but have been modified in order to be more adapted to the highly mobile vehicular environment. The main changes are as follows. The channel bandwidth have been decreased from 20 MHz channels to 10 MHz channels in order to mitigate potential problems caused by the vehicular environment. Also, functionality to allow direct peer to peer communication have been enabled meaning that no central base station is needed and the nodes connect in an Ad-Hoc fashion, outside the context of a basic service set (BSS) [5].

In Europe the upper layers are standardized in the ETSI ITS-G5 set of standards released by ETSI [19, 20]. In Fig. 2.1 the ETSI ITS example reference architecture for an ITS station is given. In this architecture, six major blocks are identified. The management block and the security block interconnects to all other blocks of the architecture. The Access block is standardized in IEEE 802.11-2012, in which IEEE 802.11p is integrated, for the MAC and PHY layers and corresponds to layers 1 and 2 of the OSI model. Above the access block the Networking and Transport block is located. This block contains, e.g., the GeoNetworking functionality [19], and corresponds to layers 3 and 4 of the OSI model. In the Facilities block several supportive functionalities are found, e.g., application support. The Facilities block corresponds to layers 5, 6 and 7 of the OSI model. The sixth block is the application block were the logic for the different ITS functionalities are located.

Several measurement campaigns have been performed in order to evaluate the performance and abilities of IEEE 802.11 based V2V communications. In [8] the problems of having non-LOS conditions in urban and suburban street intersections is studied using passenger cars. The work showed decreased performance when the transmitting and receiving antennas are out of LOS. In [21], the problems with non-LOS conditions were also identified through measurements. Heavy vehicles potentially have additional challenges compared to passenger cars since the geometry of the heavy vehicle create a situation were it is not possible to get 360 ° LOS when using a single antenna system. In [22] two different antenna positions on heavy vehicles are evaluated, antennas mounted on the rear view mirrors and the roof are evaluated and the analysis shows that the rear view mirrors are the better position. This can be due to that the cargo will create blockage for the roof antennas (since the cargo is taller than the roof of the cabin) in the back direction. In [7] it is shown that heavy trucks can create high level blockage with packet error rate (PER) higher than 90 %. These problems or challenges indicate that in order to achieve safe and reliable V2V communication several approaches to mitigate the problems are needed. This thesis presents two possible ways; choosing the transmission antenna with respect to the likelihood of having LOS conditions and by using relaying and forwarding algorithms to improve the quality of the communication.

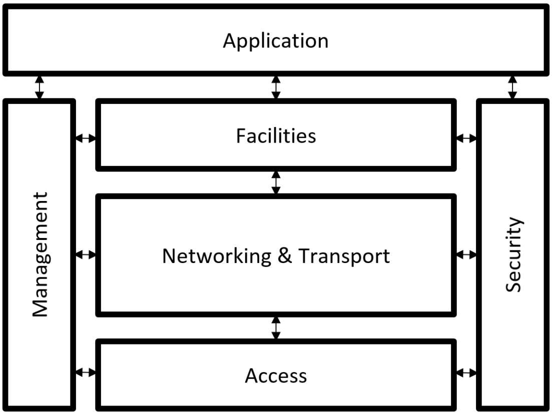

Figure 2.1: ETSI ITS-station example reference architecture.

Chapter 3
Summary of Papers

This chapter summarizes the three appended papers, starting with the antenna selection method presented in paper A, followed by the two forwarding algorithms, the Reachability Matrix forwarding algorithm and the Data Age Dependent forwarding algorithm, in papers B and C, respectively.

For the evaluation of the methods and algorithms in the following subsections a measurement campaign was conducted in order to get real world V2V communication measurement data. Four heavy duty vehicles was used during measurements, where the vehicles drove in a platooning like formation on a public highway in Sweden using adaptive cruise controls with an inter vehicle distance of approximately 22 meters and a speed of 80 km/h.

3.1 Paper A

In paper A, a transmission antenna selection method is proposed. This method is evaluated to answer the first research question on how to mitigate transmission blockage in a platooning scenario.

A method of utilizing the curvature of the road in order to select the transmission antenna with the highest probability of having LOS conditions and hence higher probability of successful transmission is proposed. The method assumes a platoon of heavy duty vehicles with antennas installed in each rear view mirror or the upper wind deflectors. It is also assumed that the leading vehicle has the ability to evaluate the yaw rate of the platoon in order to determine if the platoon is turning or not.

The transmission antenna is selected with respect to in which direction the platoon is "turning" or heading. If the heading of the platoon is evaluated to be in a turn then the transmission antenna located in the inner curve is chosen. If the platoon on the other hand is driving straight ahead, within certain limits, the method alternates between the left and the right hand side transmission antennas. By selecting the transmission antenna in this manner, the blockage caused by the cargo can to some extent be mitigated. Also, the Data Age metric is introduced in a V2V communication context for the assessment of the communication quality within the platoon. For the evaluation of the method, the communication channel between the first and the third vehicle of a four vehicle platoon is used.

When applying the method it is shown that a 150 ms Data Age deadline is missed in only approximately 50 % of the time compared to if the antenna were to be selected in a round robin fashion.

3.2 Paper B

In paper B, a novel low overhead forwarding algorithm is proposed and evaluated to answer the second research question on how to improve the age of the information in each vehicle in a platooning scenario.

The low overhead Reachability Matrix Algorithm to be used for enhanced communication quality in a platooning scenario for heavy duty trucks is proposed. The algorithm focuses on improving the overall information up-to-dateness for all vehicles within a platoon of heavy duty trucks while at the same time keeping the overhead at a low level.

The idea behind the reachability matrix forwarding algorithm is to utilize information on the current communication status within the platoon to select forwarding node/truck. Prior to each transmission the transmitting node append information describing the local nodes current understanding of the communication quality from other node's in the platoon. We call this appended information, the reachability bit vector. The reachability bit vector contains one single bit for each member of the platoon. If the bit is one it is deemed that the communication from the corresponding node is good. At the reception of a message, the receiving node extracts the reachability bit vector and updates the local reachability matrix. The reachability matrix contains information on the current communication status perceived by all nodes in the platoon, but with some delay. The local node can, by using information in the matrix, estimate if there is one or several other nodes in the platoon that could potentially benefit if the local node relays the received message. This estimation is performed in all nodes that receives the message and the one that can potentially reach the most additional nodes will perform the forwarding.

When applying the Reachability Matrix Algorithm we show by simulation that the algorithm decreases a 0.2 second data age limit miss ratio from 18 % to 11 % while at the same time only increasing the total number of messages sent within the platoon from 40 to 48.5 per second on average when compared to only sending in broadcast mode. Comparisons with two other algorithms are also reported.

3.3 Paper C

In paper C, a performance centric forwarding algorithm is proposed and evaluated to answer the second research question on how to improve the age of the information in a platooning scenario.

The high performance Data Age Dependent forwarding algorithm focuses on high performance with respect to keeping the overall Data Age in the platoon at a low level. The focus on high performance comes to a cost of utilizing more overhead, compared to the Reachability Matrix Algorithm suggested in Paper B. The algorithm utilizes high resolution communication link information for its estimation of forwarding candidates.

The rationale behind the Data Age Dependent forwarding algorithm is, as in Paper B, that a receiving node in the platoon can make a better forwarding decision if it has information on which pairs in the platoon that recently had good communication. In order to provide this information, the entire reachability matrix is distributed at each transmission event. The reachability matrix contains Data Age values for each communication pair giving information on which pairs have heard each other recently. At every reception of a message the receiving node updates its reachability matrix with the information stored in the incoming matrix. Then an estimation is made of how many additional nodes can be reached if the receiving node performs a forward. The node that can potentially reach the most additional nodes is selected to perform the forward.

Simulation show that a 0.2 s data age limit miss ratio is decreased from 18 %, in the broadcast case, to 5 % when applying the data age dependent forwarding algorithm. However, also the overhead is increased, i.e., with an increase from 40 to 54 messages per second on average for the entire four vehicle platoon. Also the size of the reachability matrix, that is piggybacked to the information message, need to be considered. For an eight vehicle platoon the size of the reachability matrix is 21 bytes, which is about four per cent of a 500 byte packet.

Chapter 4
Discussion

In this chapter I will give a discussion on the methods and results obtained and presented in the three appended papers.

First, I will clarify concerning assumptions that have been made throughout the work. Challenges exist with respect to antenna placement. During the RelCommH [23] project several antenna positions were discussed and/or evaluated, e.g., antennas on the trailer, under the truck, on the wind deflectors, on long sticks and on the rear view mirrors.

The major reason not putting the antennas or radio nodes on the trailer or on the cargo is that these objects are not under the control of the truck manufacturer and for such an important functionality as the V2V communication, the truck manufacturer want to have full control. The RelCommH project performed measurements where the antennas were mounted under the truck, but the result showed poor performance. These results are unfortunately not publicly published. Placing antennas on a truck is not only a technical challenge but also a design challenge, where the design department have quit a lot to say about the appearance, hence no long sticks will be allowed. For these reasons I argue that the rear view mirrors are, as of today, the best position to place the antennas. The rear view mirrors are positioned in such a way that the drivers shall be able to see pass the load, hence the antenna will also experience LOS condition in the back direction and of course also front direction. However, ongoing discussions in the automotive community exist on how to replace the mirrors with cameras and screens, which potentially lead to that new positions for the antennas need to be investigated.

During measurements an update rate of 10 Hz was used. In the ETSI specification for cooperative awareness message (CAM) [24] the maximum update rate is 10 Hz, which in combination with results from discussions with the two truck manufacturers in the RelCommH project led to that 10 Hz is a fair assumption. It was judged that a 10 Hz update rate will be sufficient with respect to giving input to the controller for controlling the dynamic behavior of a heavy duty vehicle driving in a platoon. Unfortunately there was somewhat secrecy about what update rate is necessary, possibly due to competitive matters. This lead to that 10 Hz shall only be seen as a possible candidate for the update rate in a platooning application.

In order to assess the different antenna positions, methods and algorithms for improved V2V communication, the Data Age metric was designed within the RelCommH project. The Data Age is basically the age of the information, sampled at a sending node, but used in a receiving node. A time stamp is attached to a sample from the time instant of sampling, while at the receiver the time in the time stamp is subtracted from the current time and the age of the information is obtained. This assumes that the clocks in the nodes can be synchronized with enough accuracy. Another incentive to use the Data Age metric was to have an online metric that control engineers can use as an evaluation metric for the current information situation as input to the platooning application controllers.

For the forwarding algorithms we also introduce the message intensity metric. The metric is important in order to keep track of how much a certain algorithm will load the channel. In our measurement setup we used four vehicles, and in that case the message intensity is perhaps not that important. However, if driving on a five lane highway and passing an exit or entrance ramp, then keeping the message intensity at a low level can be of utmost importance in order for the system not to break down. IEEE 802.11 based V2V communication utilize CSMA/CA, whose performance deteriorates dramatically when the channel busy time passes somewhere around twenty five percent according to [25].

The analysis of the collected measurement data indicate that in order to achieve reliable V2V communication, steps need to be taken. In the appended papers a few suggested steps towards more reliable communication are given. However, the wireless channel have stochastic properties and packets can be lost. This implies that the applications that rely on V2V communication always need strategies to deal with under performing communication. My understanding is that the work need to proceed in order to improve the reliability of the communication. All of the appended papers assumes IEEE 802.11 based V2V communication, where a contention based MAC protocol, i.e. CSMA/CA, is used. Ongoing discussions in the research community indicate that device to device (D2D) communication in the coming 5G can potentially be an alternative to IEEE 802.11 based V2V communication [26]. In the 5G system, even in D2D, the MAC layer control can potentially be centralized, implying guaranteed channel access. The 5G system also have access to additional spectrum that can potentially be better suited for vehicular communication. The future will give the answers on what V2V technology will dominate.

Simple measures can make a difference as for the curvature based transmission antenna selection method, which is a simple and yet an effective way of increasing the probability of having LOS conditions for heavy vehicles driving in a platoon. Information needed to determine if the vehicle is in a turn already exist on the intra-vehicle communication bus, hence no extra sensors would be necessary for the method to be implemented. This lead to that the method can potentially be a cost efficient way of increasing the V2V communication quality in the scenario where the vehicles drive in a platoon on a highway with moderate turning.

A more complex measure that will utilize more memory, processing power and engineering skill is the forwarding algorithms presented in Papers B and C. The algorithms are more complex than the transmission antenna selection method but they also come with good performance with respect to keeping the Data Age at a low level, while still keeping the message intensity low. An interesting investigation would be to combine the forwarding algorithms with the antenna selection method, which is one of my suggestions for future investigation.

Chapter 5
Conclusions and Future Work

Conclusions

In this thesis two approaches of improving the performance of V2V communication in a platooning scenario for heavy duty vehicles are presented.

The transmission antenna selection method selects the transmission antenna based on the road curvature in order to increase the probability of having LOS conditions, hence also improving the probability of successful transmissions. Also, two forwarding algorithms are presented. The Reachability Matrix forwarding algorithm has a strong focus on keeping the overhead at a low level, while at the same time improving the quality of the communication in the entire platoon. The second algorithm is the Data Age Dependent forwarding algorithm where focus is more on high performance, leading to somewhat higher overhead.

The transmission antenna selection method show potential of mitigating blockage caused by the cargo on the trucks, which lead to improvement of the Data Age in the investigated communication pair. Both forwarding algorithms improves the communication quality by lowering the Data Age for all vehicles in a platooning scenario compared to if the communication only relies on broadcast.

Future Work

For the future it would be interesting to combine the transmission antenna selection method with one or both of the forwarding algorithms, and evaluate this combined algorithm in a widely spread simulation environment. This simulation environment could potentially be VEINS [27] in combination with the PLEXE [28] extension.

It would also be interesting to perform V2V communication measurements on a platoon of heavy vehicles consisting of at least six vehicles and use the retrieved measurements to create a V2V channel model for the platooning scenario. The retrieved channel model would then of course be used as input to the above mentioned simulation.

Also, taking the step from the simulation environment to the physical environment and implement the combined algorithm in order to verify it in a physical environment would be interesting.

References

[1] A. B. Nkoro and Y. A. Vershinin, "Current and future trends in applications of intelligent transport systems on cars and infrastructure," in *2014 IEEE 17th International Conference on Intelligent Transportation Systems (ITSC)*, 2014, pp. 514-519. (Cited on page 1.)

[2] A. T. O'Connor and J. C. Falcocchio, "A framework for the deployment of intelligent transportation systems in a multi-agency urban environment.", in *Transportation Research Board 94th Annual Meeting. No. 15-0524.* 2015. (Cited on page 1.)

[3] W. Danping, K. Hu, and X. Han, "Research on development and model of intelligent transportation systems.", in *2015 International Conference on Automation, Mechanical Control and Computational Engineering. Atlantis Press,* 2015. (Cited on page 1.)

[4] C. Bergenhem, H. Petterson, E. Coelingh, C. Englund, S. Shladover, and S. Tsugawa, "Overview of platooning systems," in *19th ITS World Congress*, Vienna, Austria, 2012. (Cited on page 1.)

[5] "IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments," in IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009), ed, 2010, pp. 1-51. (Cited on pages 1, 6, and 7.)

[6] A. Dávila and M. Nombela, "Sartre - safe road trains for the environment reducing fuel consumption through lower aerodynamic drag coefficient", in *SAE Technical Paper*, 2011-36-0060, 2011. (Cited on page 1.)

[7] K. Karlsson, C. Bergenhem, and E. Hedin, "Field measurements of IEEE 802.11p communication in NLOS environments for a platooning applica-

tion," in *2012 IEEE Vehicular Technology Conference (VTC Fall)*, 2012, pp. 1-5. (Cited on pages 2 and 7.)

[8] T. Mangel, M. Michl, O. Klemp, and H. Hartenstein, "Real-world measurements of non-line-of-sight reception quality for 5.9GHz IEEE 802.11p at intersections," in *Communication Technologies for Vehicles.* vol. 6596, T. Strang, A. Festag, A. Vinel, R. Mehmood, C. Rico Garcia, and M. Röckl, Eds., ed: Springer Berlin Heidelberg, 2011, pp. 189-202. (Cited on pages 2 and 7.)

[9] Intelligent Transportation Systems (ITS) Standards Program Strategic Plan for 2011-2014, (2015-11-10), Retrieved from http://www.its.dot.gov/standards_strategic_plan/ (Cited on page 5.)

[10] SeeMe Crossing, (2015-06-16), Retrieved from http://www.amparosolutions.se/en/product/seeme%C2%AE-crossing (Cited on page 5.)

[11] N. Suganuma and Y. Hayashi, "Development of autonomous vehicle-Overview of autonomous driving demonstration in ITS world Congress 2013.", in *2014 11th IEEE International Conference on: Informatics in Control, Automation and Robotics (ICINCO)*, vol. 2, 2014, pp. 545-549. (Cited on page 5.)

[12] A. Festag, "Cooperative intelligent transport systems standards in europe," *IEEE Communications Magazine*, vol. 52, 2014, pp. 166-172. (Cited on page 5.)

[13] P. Szczurek, B. Xu, O. Wolfson, and J.P. Lin, "Estimating relevance for the emergency electronic brake light application," in *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 4, 2012, pp. 1638-1656. (Cited on page 5.)

[14] The SARTRE homepage, (2015-11-10), Retrieved from www.sartre-project.eu (Cited on page 6.)

[15] J. B. Michael, D. N. Godbole, J. Lygeros, and R. Sengupta, "Capacity analysis of traffic flow over a single-lane automated highway system," *ITS Journal - Intelligent Transportation Systems Journal*, vol. 4, 1998, pp. 49-80. (Cited on page 6.)

[16] W. F. Torrey and D. Murray, "An analysis of the operational costs of trucking: 2014 Update", *Technical report, American Transportation Research Institute*, (2015-06-16), Retrieved from http://atri-online.org/2014/09/24/3708/ (Cited on page 6.)

[17] S. Tsugawa, "Results and issues of an automated truck platoon within the energy ITS project," in *2014 IEEE Intelligent Vehicles Symposium Proceedings*, 2014, pp. 642-647. (Cited on page 6.)

[18] A. Davila, E. Aramburu, and A. Freixas, "Making the best out of aerodynamics: platoons," in *SAE Technical Paper*, No. 2013-01-0767, 2013. (Cited on page 6.)

[19] ETSI, "Intelligent Transport Systems (ITS); Vehicular communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality," in *ETSI TS 102 636-4-1 V1.1.1*, ed, 2011. (Cited on page 7.)

[20] ETSI, "Intelligent Transport Systems (ITS); Communications Architecture", in *ETSI EN 302 665 v1.1.1* (2010-09), 2010. (Cited on page 7.)

[21] A. Böhm, K. Lidström, M. Jonsson, and T. Larsson, "Evaluating CALM M5-based vehicle-to-vehicle communication in various road settings through field trials," in *The 4th IEEE LCN Workshop On User Mobility and Vehicular Networks (ON-MOVE)*, Denver, CO, USA, Oct. 2010, pp. 613-620. (Cited on page 7.)

[22] C. Bergenhem, E. Coelingh, R. Johansson, and A. Tehrani, "V2V communication quality: measurements in a cooperative automotive platooning application," in *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.*, vol. 7, 2014, pp. 462-470. (Cited on page 7.)

[23] The RelCommH project, (2015-12-08), retrieved from http://www.sp.se/en/index/research/relcommh/sidor/default.aspx (Cited on page 13.)

[24] ETSI EN 637-2: ITS; Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, June 2012. (Cited on page 13.)

[25] A. Böhm, M. Jonsson, and E. Uhlemann, "Performance comparison of a platooning application using the IEEE 802.11p MAC on the control channel and a centralized MAC on a service channel," in *2013 IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2013, pp. 545-552. (Cited on page 14.)

[26] H. Tullberg, Z. Li, A. Hoglund, P. Fertl, D. Gozalvez-Serrano, K. Pawlak, P. Popovski, G. Mange, and O. Bulakci, "Towards the METIS 5G concept: First view on Horizontal Topics concepts." in *2014 IEEE European Conference on Networks and Communications (EuCNC),* 2014, pp. 1-5 (Cited on page 14.)

[27] VEINS, (2015-11-19), Retrieved from http://veins.car2x.org/ (Cited on page 17.)

[28] PLEXE, (2015-11-19), Retrieved from http://plexe.car2x.org/ (Cited on page 17.)