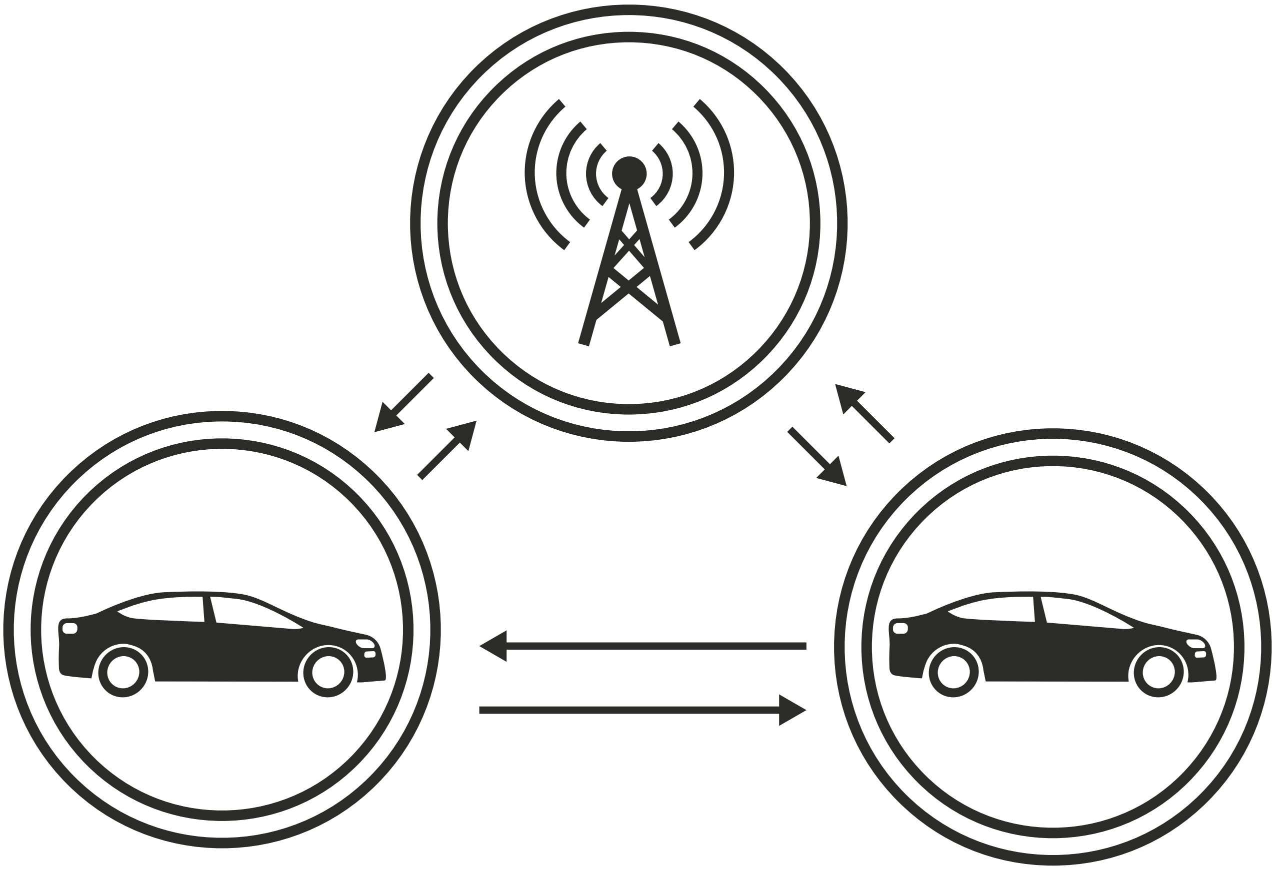
CHALMERS



Real world applications and analysis of V2X communication in the 2016 Grand Cooperative Driving Challenge

Master's thesis in Complex Adaptive Systems

BJÖRNBORG NGUYEN

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2016

MASTER'S THESIS IN COMPLEX ADAPTIVE SYSTEMS

Real world applications and analysis of V2X communication in the 2016 Grand Cooperative Driving Challenge

BJÖRNBORG NGUYEN

Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous Systems
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2016

Real world applications and analysis of V2X communication in the 2016 Grand Cooperative Driving Challenge
BJÖRNBORG NGUYEN

Master's thesis 2016:02
ISSN 1652-8557
Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous Systems
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: +46 (0)31-772 1000

Chalmers Reproservice
Göteborg, Sweden 2016

Real world applications and analysis of V2X communication in the 2016 Grand Cooperative Driving Challenge
Master's thesis in Complex Adaptive Systems
BJÖRNBORG NGUYEN
Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous Systems
Chalmers University of Technology

ABSTRACT

This master thesis analyses the performance of one particular existing open software solution for vehicular communication for intelligent transport systems which is the GeoNetworking library and Vehicle adapter which abide the European Telecommunications Standards Institute's directives and regulations regarding vehicular communication under the name of ITS-G5. In terms of performance, latency and the throughput capabilities of the software were observed and studied in both controlled environment and real world case scenario. This study greatly benefited from the i-game's project: 2016 grand cooperative driving challenge, where several automated vehicle systems equipped with vehicle communication systems were participating in three distinct scenarios demonstrating the different applications of cooperation using vehicular communication; these scenarios are emergency vehicle-, intersection-, and merging scenario. Data was gathered through benchmarking software tools in a simulated environment and interviews with the participating teams.

The results of the Vehicle adapter on the GeoNetworking library and proposed hardware solution shows that the latency was less than 0.005 s when neglecting the data transfer time between the layers of the system while throughput benchmarked at 98.41 messages per second at ideal settings. On the other hand, the findings of the benchmarked throughput may be improved since it contradicts the observed performances of participating vehicle systems in the i-game's driving challenge. Still, the proof of concept of vehicle communications was clearly demonstrated on a small scale with nearly no signs of performance problems during the competition.

From interviews, some teams in the competition expressed their concerns regarding the vehicle communication in various aspects. One of the pressing issues is the information theory and game theory; fundamentally down the question: can your system trust other's broadcast information for collaboration purposes? They were also concerned for the user integrity and network security which are strongly associated with network communication regardless of the applications.

However, vehicle communications show significant promises and contributions to new types of application in cooperative behaviors in both automated- and autonomous vehicles. The most obvious application would be platooning which would greatly benefit from the shared information as well handshaking protocols for complex scenarios as platoon merging. Further on a macroscopic level, it could counteract the traffic congestion as well reduce the fuel consumption of the vehicles.

Keywords: ITS-G5, vehicle communication, V2V, V2I, V2X, GeoNetworking, 2016 grand cooperative driving challenge

ACKNOWLEDGEMENTS

With this master thesis of mine, it will hopefully put an end to my five years of study at Chalmers University of technology. As this chapter of my life closes, I may start writing the next one and continue my academic career to pursue my ambitions and dreams to achieve full-fledged life. I stand at this point as a proud son of my father, Anh Truong and my mother, Thi Hue Nguyen who always encouraged me press on no matter what. In the moment as I am writing this, my mother is no longer alive but her fierce spirit still resides within me and will always remind me to be ambitious and goal oriented.

The lovely illustration on the front page among few more are created by my childhood best bud, Henrik Giang, whom I share a dear past with. We used to jump around imagining us as fictional character armed with deadly weapons, playing video games until one of us fell asleep, and simply be there for each other. As grown-ups now, we are currently walking down on different paths straying away from our shared road. But no matter what, I am thankful for our long lasting friendship.

As a confused and lost teenager, I met Roger Almblad who was my teacher in mathematics and physics courses during my time in the gymnasium. I am forever grateful for his deep insight, inspiring lectures and pieces of life-changing advice. It's mainly thanks to Roger, I have started walking down on this academic career. I hope Roger will keep on inspiring many more generations to come as he did to me.

I also want to mention a good friend of mine, Mattias Eliasson, whom I befriended on my first day as a bachelor student. During my five years of study in the university I have had ups and downs, and more importantly, a friend who kicked my ass for every time I was being lazy, ignorant, or procrastinating. I owe him my deepest gratitude and can only hope that I can repay this favor one day.

Last but not least, I would to acknowledge my colleagues, Ivo Batkovic, Björn Mattsson, Johan Bergström, and Mats Svensson, during the grand cooperative driving challenge and also, Fredrik von Corswant and Arpit Karsolia from Revere. Never have I asked for so much help when it boils down to software from one single person and consistently, time after time, fixing my problems in a humble manner. My hat goes off to you, Christian Berger. My one and only special thank goes to my supervisor Ola Benderius who has guided me through this master thesis right from the beginning to the very end of it. Not everyone can tolerate reading my thesis as many times as Ola has done it and I am deeply and sincerely grateful to him for that.

Contents

1 Introduction

Sophisticated automated and autonomous vehicles have in recent years became a reality in both scientific research and the industrial development [1]. One of the most important milestones within autonomous vehicles would be a completely driver-less vehicle system. This implies a fully adaptive autonomous vehicle system should to handle any traffic environment such as highway environment or city environment.

Acquiring data from the environment is thus crucial to support such refined behavior. Both autonomous and automated system are and will be bounded and dependent on its sensors and data gathering. Furthermore, information theory is getting more relevant in this field of engineering as the data information becoming more complex. There are several ways to gather information from the surroundings. The most common solutions are lidars, radars, and sonars. Vision sensors are more widely used in various fields of computing as artificial neural networks are applied as an image processing component.

Another approach to gather information is to introduce a communication among intelligent vehicles, as inspired by modern wireless network technology. Such vehicle communication is more commonly known as *vehicle–to–vehicle* (V2V) or *vehicle–to–infrastructure* (V2I) communication. This allows for continuous data sharing to the surrounding environment and vehicles. Typical examples of data that are shared include position, velocity, and vehicle intentions. By being able to access such data from other agents, a vehicle can more easily be capable of complex behavior such as vehicle cooperation in platooning and merging.

This type of technology would enable a new type of cooperation among intelligent vehicle such vehicle platooning. There are potential benefits of vehicle platooning such as reduced fuel consumption, reduced traffic congestion, and improved safety. A classic example is a platoon of large heavy trucks where vehicle system cooperation could reduce the distance between the vehicle and ultimately decrease the fuel consumption of the platoon.

However, in recent years, different regions in the world have proposed their own standards within vehicle communication, both concerning network protocols and message formats. Europe is on its way to standardizing the vehicular communication which is proposed by the *European Telecommunications Standards Institute* (ETSI). The suggested network protocol is the *geocast* protocol, which will broadcast messages openly with the rest of the network without any handshaking. The communication is simply bounded by the geographic location of the nodes, which might be preferable in very dynamic topologies [2].

There are two layers in the access layer of the communication stack that are in interest for standardizing vehicle communication. These are the physical layer and data link layer that allows data to be exchanged on the frequency band 5.9 GHz between mobile stations. This is grouped under the accumulative name ITS-G5 (Intelligent Transportation System) which is an approved amendment to the IEEE 802.11 protocol namely Wireless Access in Vehicular Environment (WAVE).

The European Union has put a great effort in stimulating the research and development on vehicular communication, in particular for vehicle cooperation purposes. Therefore, the project i-Game was carried out with the purpose of hosting and arranging the competition referred to as the Grand Cooperative Driving Challenge (GCDC). The competition put special emphasis on vehicle communication by demonstrating advanced vehicle cooperation behavior. Previously, an earlier version of GCDC was run in the year 2011 with the focus on simple platooning. However, in 2016, the competition put an additional technical moment of a merging of two vehicle platoons for the purpose of initiating development of vehicle communication technology in Europe. In order to merge the two platoons successfully, high-level interaction among the intelligent vehicles is required.

1.1 Research questions

This thesis will address real world scenarios for vehicle communication applications particularly vehicle cooperation with the help of i-Game's driving challenge scenarios of merging and intersection. The research question is how feasible it is to use vehicle communication in real-world highway merging and traffic intersection. The main aspects that will be studied are the time response (latency) and the message congestion (throughput) of existing solutions of ITS-G5. The purpose of the thesis is to provide knowledge and understanding within the vehicular communication and further to provide analysis and constructive criticism to aid further development of vehicle communication technology.

The evaluation of the system will be conducted in a combination of interviews with the participating teams in 2016 GCDC and simulated environment test of the communication stack. In the real world scenario case in GCDC, the communication network will consist of maximum twelve nodes interacting with each other and study how well every team's chosen communication stack solution perform under different scenarios throughout the event.

1.2 Limitations and scope

There are commercial off-the-shelf solutions for vehicular communication on the market. However, many commercial solutions are hard to modify both hardware- and software-wise which may pose difficulties as a developer. Clarity and open solutions to software implementations are valued highly in research, and thus commercial solutions will not be considered in thus thesis.

2 Background

This chapter will briefly review the vehicular communication history, vehicle communications standards, and the i-Game events. The history of wireless vehicle communication technology is deeply intertwined with intelligent vehicle development and has, therefore, a shared history. The idea of having automated vehicles is very old but it was only past decades ago that technology made it possible to implement these ideas practically. The development of an adaptive automated vehicle requires practices and theories from many distinct fields of engineering and mathematics such as electrical engineering, mechanical engineering, information theory, and software engineering. Therefore creating a fully adaptive self-driving vehicle is a complicated and complex problem.

2.1 History of vehicle to vehicle communication

The intelligent Transportation Systems (ITS) was the result of a workshop held in Dallas, Texas, the year 1990 where the participants came up with conceptual ideas with the purpose of improving the transportation efficiency with help advanced technology. This would involve new technology and thus advance the development in computing, sensors, information theory and mathematical methods [3]. The concepts were widely accepted the year later as they received funding for development and testing spanning several years. ITS has ever since been involved in development in various areas but their main contributions have been to safety, mobility, and sustainability.

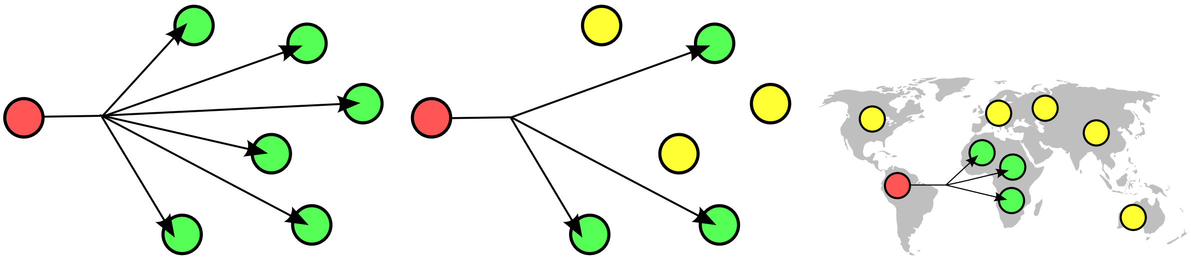
The conceptual idea of inter-vehicle communication was already existing since the inception of ITS. The idea became more apparent and was visualized when the Intermodal Surface Transportation Efficiency Act called for an intelligent automated highway vehicle prototype [3]. The project went under the name "Automated Highway System Program" with the intention to develop a fully operational test track along with specially equipped intelligent vehicles that could travel together under the influence of a central computer controller by the year 1997.

Shortly after, the Intelligent Vehicle Initiative was founded and authorized with the main objective to prevent distraction-affiliated accidents and facilitate accelerated deployment of crash avoidance systems. This gave rise to the further development of driver assistant solutions that were based on existing vehicle systems and infrastructure cooperation interaction. During the development of these driver assistance products, the direction of telecommunications technology shifted towards information sharing among vehicles and infrastructure [4].

In response to the 10th Intelligent Transportation Systems World Congress, Federal Communications Commission allocated and reserved the 75 MHz frequency band for dedicated short range communications in favor of research purposes. The main motive was to improve the transportation safety and mobility. The past research and newly allocated frequency band made V2V and V2I communication that had safety and mobility applications possible.

2.2 Network routing protocol

As vehicle communication is a type of ad-hoc network, it is necessary to decide upon what network routing protocol standard to use. A network protocol standard is an agreement among the clients and servers, which dictates how data packets are routed within any network. Particularly in mobile ad hoc networks, the clients



(a) *Broadcast* (b) *Multicast* (c) *Geocast*

Figure 2.1: *The diagrams illustrate the different core functionalities and features of broadcast, multicast, and geocast. Broadcast routing protocol sends message to the rest of network. Mutlicast routes its message to every node that actively listens. Geocast has an active geographic constraint on the recipient nodes making it able to target a specific group of nodes.*

(nodes) have to announce their presence in their neighboring network and declaring that they are listening to broadcasts. The main reason is that the nodes are not in particular familiar with the topology of the networks due to the dynamic nature of mobile ad hoc networks.

To tackle this problem, researchers have proposed a range of various network routing protocols in V2X communications. The proposals are mainly based on the factors of the system architecture, geographical environment, applications, and challenges. V2X routing protocols can be divided into five categories, which do not focus on fixed infrastructure of the network. These five categories may be considered as listed: (i) topology-based routing protocols, (ii) position-based routing protocols, (iii) cluster-based routing protocols, (iv) geo–cast-based routing protocols, (v) multicast-based routing protocols, (vi) and broadcast-based routing protocols. Three of them are illustrated in Figure 2.1 demonstrating their core functionalities and features. Due to the high mobility of the network nodes, it makes the topology very dynamic with frequent disconnections. This will create many difficulties and render several network protocols inefficient [5]. Sharef et al., discuss various challenges and limitation of different routing protocols for V2X. They concluded that the position-based routing and geo-casting are more suited than the other routing protocols for purpose of vehicular ad-hoc networks due to environmental limitations and circumstances.

Furthermore, in an extensive survey in vehicular communication ad hoc routing protocols [2], Al-Sultan et al., address the major problems with the wireless networking which are still relevant at this point. Many of the existing routing protocols are designed for other purposes and in a different environment than vehicular communication which may prove difficulties in implementing them to that specific cause.

Ultimately how vehicle communications stand today concludes that it is still experimental to an extent. Some implementations and analysis have been conducted but there is still room for more research and development in vehicular communication or mobile ad hoc networks.

2.3 European Telecommunications Standards Institute

European Telecommunications Standards Institute (*ETSI*) was established by European Conference of Postal and Telecommunications Administrations and officially recognized by European Commission year 1988. The purpose of the organization is to publish and standardize Information and Communication Technologies (ICT) within Europe. The organization consists of more than 800 member organizations from all over the world, including the world's leading companies and innovative research and development organizations. Ever since the establishment of ETSI, they have formalized and produced roughly 30000 standards.

The standards are produced through an open approach: all members are involved in all the stages of the making of a standard, and consensus among the members throughout the process. Different stakeholders will, therefore, collaborate and their cooperation will result in successful and more accepted standards in the respective fields of technology.

Since a few years back, ETSI has released and established several standards regarding ITS. The communication stack is greatly affected by these standards explicitly the networking layer protocol (*GeoNetworking*) [6], Basic Transport Protocol (BTS) [7], specific message format and specifications of Cooperative Awareness Message (CAM) [8] and Decentralized Environment Notification Message (DENM) [9], and the messages' Common Data Dictionary (CDD) [10]. These standards intend to ensure the communication among vehicles in

Europe despite having different manufacturers, developers, and producers.

2.4 2016 Grand Cooperative Driving Challenge

The 2016 challenge is funded and managed under the project Interoperable Grand cooperative driving challenge (GCDC) AutoMation Experience which is supported and acknowledge by the European commission. The main purpose of the project is to stimulate the implementation and interoperability of wireless communication based automated driving. The project officially started in October 2013 with an end date in September 2016. Within that time frame, the project had wished to achieve: (i) unified functional architecture and requirements for an interoperable cooperative automated driving platform, (ii) supervisory control system and interaction protocol for cooperative automated driving applications, (iii) standardized interaction messages for interoperable wireless communications based automated driving, and (iv) validation and verification tools and events for performance and interoperability testing of cooperative automated driving applications.

The project was demonstrated at the end of May 2016 in Helmond, Netherlands, on the highway A270 to Eindhoven. There were 11 participating teams from many parts of Europe, competing with their automated vehicles. The demonstration had 3 different types of scenarios demonstrating different application of vehicular communications namely *emergency scenario*, *intersection scenario*, and *merging scenario* (including platooning). In the two last-mentioned scenarios intended to have automated vehicle with incorporated vehicle communication system. With help of the communication to other vehicles as well to the infrastructure, the cooperation among the participants should improve.

The emergency vehicle scenario This scenario, unlike the other two, does not require automation functionality of the participating vehicles. An emergency vehicle (EV) will approach two condensed platoons of intelligent vehicles. The overview of the scenario can be seen in Figure 2.2. It intends to demonstrate how cooperative vehicles can resolve and handle unexpected traffic situation that is common in today's traffic. One can abstract the scenario into 4 stages: EV approaching-, EV passing-, gap closing-, and the end phase.

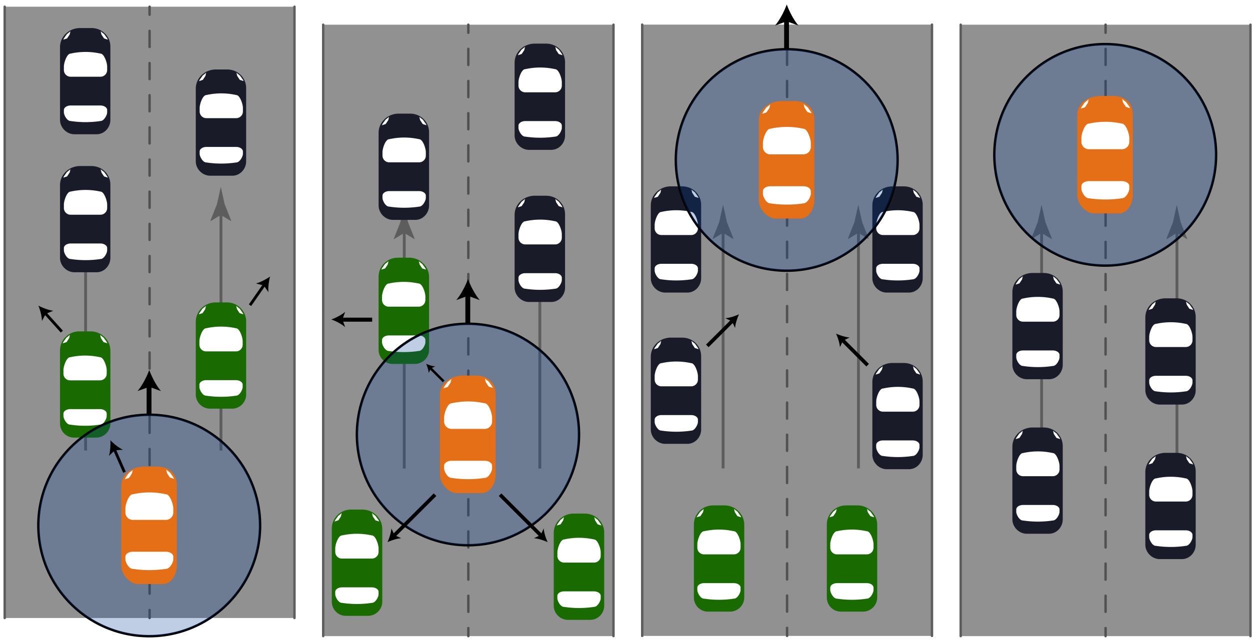
The whole scenario starts off with an EV approaching a congested traffic situation. The congested traffic will travel at $50\,\mathrm{km\,h^{-1}}$ in both lanes while the EV approaches at $80\,\mathrm{km\,h^{-1}}$. All participants will have their communication system active and will passively listen for emergency signals. The EV will continuously broadcast its emergency signal and as soon the rear-most vehicle receives the signal, the scenario is initiated. Optionally, participants may forward the message forward to the rest of the traffic in this scenario.

In the broadcast notification message from EV, it contains the practical information of what lane the EV intends to pass through. The cooperative platoons will act upon the message, lowering their speed to $40\,\mathrm{km\,h^{-1}}$ as well adapting their position by moving to the right or left thus creating a safe passage gap for the EV. When the EV passes through, the platooning vehicles will resume their position, speed, and status thus closing the gap they just created for the EV. The scenario ends when all participants stop receiving the notification message from the EV.

The intersection scenario The participants of 2016 GCDC are expected to have automated vehicles to execute this intersection scenario correctly. In a T-crossing, two participants and a reference vehicle will enter the intersection simultaneously as seen in Figure 2.3. The reference vehicle is always approaching from a side road as depicted in the figure. The scenario may be divided into three stages: initialization, intersection, and exit. The two approaching participants should reach $30\,\mathrm{km\,h^{-1}}$ upon reaching the competition zone and thereafter adaptively reducing their speed allowing the reference vehicle to pass the crossing safely. An RSU is added in the scenario for reproducibilities purposes as well helping with scenario execution in message broadcasting.

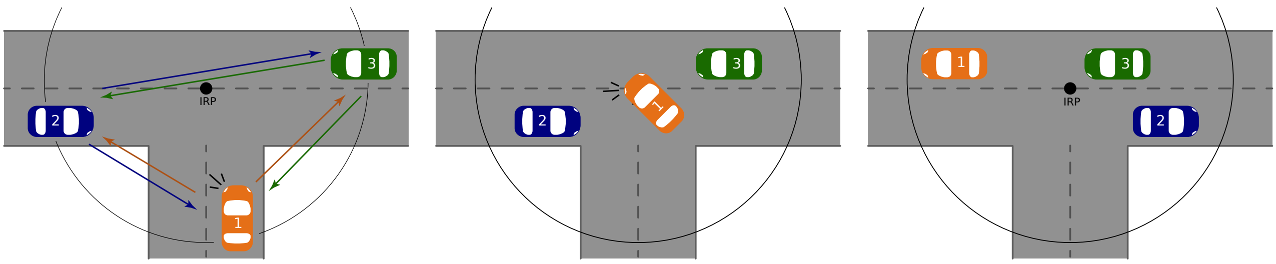
Upon receiving the start signal from the RSU, the competitors are to enter the competition zone with $30\,\mathrm{km\,s^{-1}}$ simultaneously. All participants are responsible for producing their own prediction model and may broadcast their estimated time of arrival to the intersection (with respect to the intersection reference point, IRP) for synchronization purposes.

While in the competition zone, the participants will approach the intersection where the reference vehicle will intercept the two. The automated vehicles will need to predict this accurately in their prediction models as they need to provide a safe behavior. As the reference vehicle has safely crossed the intersection, the competitors will need to exit the competition zone. When all vehicles exit the competition zone, the scenario will end.



(a) *EV approaching* (b) *EV passing* (c) *Gap closing* (d) *End*

Figure 2.2: *The different stages of the emergency scenario in 2016 GCDC are depicted here. In this scenario, an emergency vehicle (EV) is passing through two lanes of cooperating platoons with the help of V2V communication. The scenario initialises with both platoons traveling at* $50\,\mathrm{km\,h^{-1}}$ *occupying the left and right lanes, forming two platoons of vehicles. The EV will send notification messages to the platoons, informing them that the EV would want to pass through, on a specific lane. As the EV approaches with a speed of* $80\,\mathrm{km\,h^{-1}}$*, the platoons will need to open a gap as well lowering their speed to* $40\,\mathrm{km\,h^{-1}}$ *producing a safe passage for the EV. As soon the platoon vehicles stop receiving the message, starting from the tails of the platoons, they will resume their normal state and synchronize the speed and position in their platoon.*



(a) *Initialization* (b) *Intersection* (c) *Exit*

Figure 2.3: *The 2016 GCDC intersection scenario is illustrated here in 3 separated stages. The scenario is based on platooning virtually serving as a base for the speed control behavior. As the participants approach the intersection, the are supposed to reduce their speed in order to let the reference vehicle to pass safely. The reference vehicle is always positioned in the side road as depicted in the figure. An RSU is placed in the intersection reference point (IRP) for reproducibilities purposes while reinforcing the broadcasting.*

The merging scenario Like the intersection scenario, this scenario requires the automation functionality from the competitors. The merging scenario is arguably the most complicated and complex scenario in the 2016 GCDC due to the expected criteria of cooperative behavior from the participants. The cooperation among the participating vehicles will be achieved with the help of V2V communication which is one of the main purposes of the i-Game project. In this particular scenario serves as an extension of the previous 2011 GCDC main scenario namely the platooning scenario. The general stages of the merging scenario are illustrated in Figure 2.4. It may be abstracted into 4 stages: pace making-, pairing-, merging-, and end phase.

There are two platoons of vehicles involved in the scenario along with two reference vehicles (Organisation Pace Car, *OPC*) serving as the platoon leaders of each platoon. The OPC will also simulate the road work situation, acting as the broadcasting RSU. Each of the platoons is managed separately and have different starting time. When the later platoon has caught up, side by side occupying both lanes, the OPCs initiate the merging scenario by simulating the road work warning. At this point, the competition has started and first stage: the pace making phase is initiated. The platoons reduce their speed to $60\,\mathrm{km\,h^{-1}}$. This will prompt OPC in the left lane to send a merge request.

All the vehicles will try to pair up and handshake with each other and thus enter the pairing phase of the scenario. In this stage, the right lane (B) will, in parallel, pair themselves to the left lane (A) while reducing their speed further to $40\,\mathrm{km\,h^{-1}}$. This is done in a forward manner, for example as referenced in Figure 2.4b, vehicle 2 will pair up with vehicle 0 due to the reasons that it is either in parallel or occupying the left side of the gap between vehicle 0 and vehicle 2. The algorithm applies sequentially for all vehicles in the right lane (B). In the end, resulting in finding the backward pairing partner for the vehicle in the right lane (A) while finding the forwarding pairing partner for left lane (B) as well. As the pairing is confirmed by their partners (e.g. both vehicle 2 and vehicle 1 has confirmed their pairing with each other) all vehicles in the right lane (B) will widen the gap in front; making it possible for their partner vehicle to merge in.

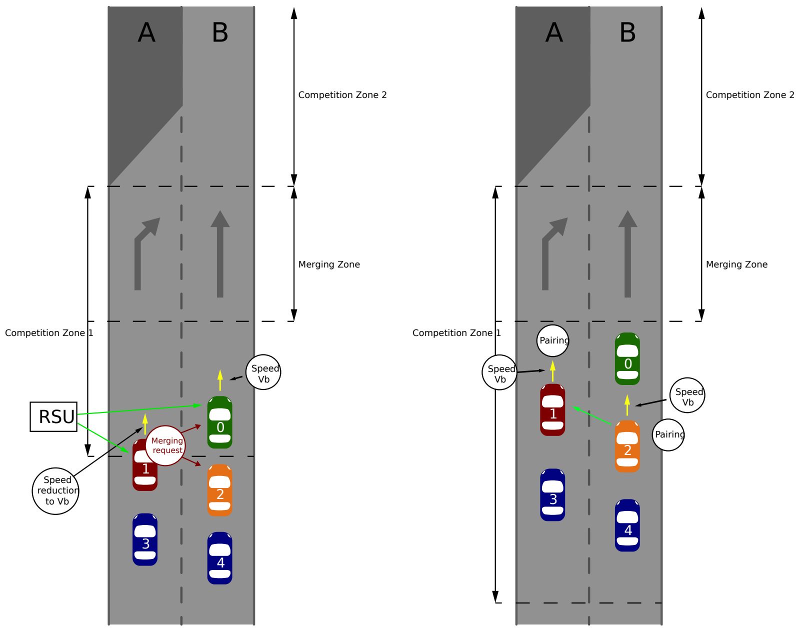
As the parallel pairing is done, the sequential pairing and merging phases commence which will put most of the focus of the platoon leader in left lane A. Only the leader in the right lane A may do the pairing and merging in this phase. Selection of the forward pairing partner for the merging vehicle is simply chosen by the vehicle in front of the backward pairing partner, e.g. the vehicle 1 will forward pair with vehicle 0 since it is in front of its backward pairing partner vehicle 2 which can be seen in Figure 2.4c. When the gap is considered safe by the gap-making vehicle, they will broadcast a safe to merge (STOM) flag, essentially the green light for the merging vehicle. As the merging vehicle is done pairing and merging, it will pass on the leadership to the foremost vehicle in the lane A and algorithm sequence is re-initiated recursively until platoon in the left lane A is completely merged into platoon B. This creates a zipper-like behaviour when the merging and ending up with one platoon on the highway after the merge.

3 Method

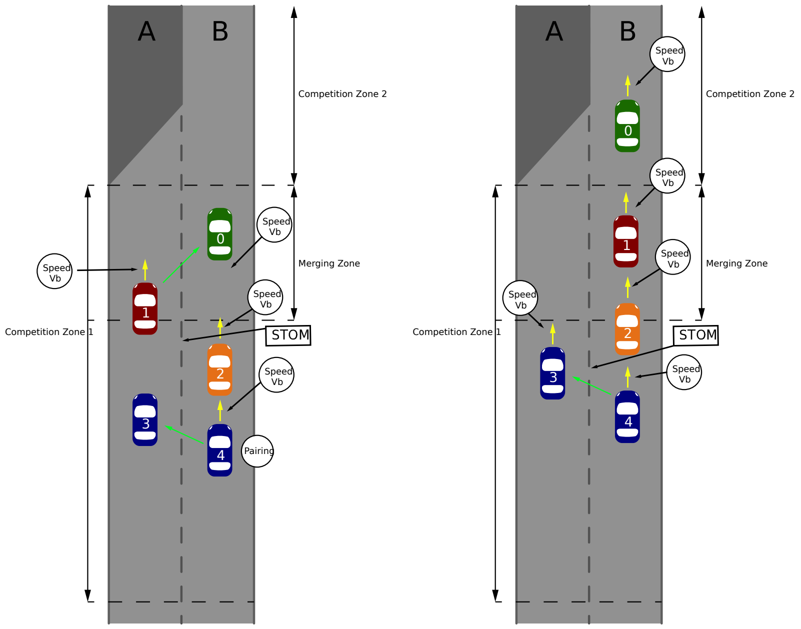
In this chapter, a technical explanation for each system component will be given both for hardware and software implementations. A description for the different message set will also be explained. As for the thesis, the research questions will be formulated and posed as further how information will be gathered and collected in the form of interviews.

3.1 System description

The communication system is deliberately designed as an encapsulated system in such way to be compatible with many different vehicle controller systems. The main reason is to ensure the vehicular communication is within one common protocol standard thus ensuring the compatibility of the V2V communication of every vehicle. The abstract schematics can be viewed in Figure 3.1 and the hardware in Figure 3.2. The main role of the stack is to handle the standard protocols to encode and decode the messages to and from the main vehicle controller system. The bits and bytes of messages will be broadcast and received through an antenna operating in the ITS frequency band of 5.9 GHz band. The vehicular communication data traffic in V2X has to be supported by the wireless network drivers, e.g. supporting the ITS frequency band. There is a data link layer entity for handling and parsing the outgoing and incoming Ethernet packets to User Datagram Protocol (UDP) packets between the network transport layer. The UDPs will contain the BTP packets according to the standards specified by ETSI. BTP packets will contain the message header which is the key in GeoNetworking



(a) *Pace making* (b) *Pairing*



(c) *Merging* (d) *End*

Figure 2.4: *The different stages of the merging scenario can be seen here. The four different stages are illustrated in the figure: pace making-, pairing-, merging-, and end phase. The scenario initiates through two separate platoons occupying a road side by side. Both platoons will be lead by two reference vehicles (Organisation Pace Car, OPC) which will handle all of the DENM broadcasts acting as an RSU simulating road work environment. This will prompt a need for platoon merging, which will be initiated by a merge request by the platoon leaders; resulting in the platoons to merge in a zipper-like manner. The pairing dictates the merging order as well the final position in the final platoon emerging from the scenario. Merging is only possible when a safe to merge (STOM) flag is broadcast by the responsible paired up partner.*

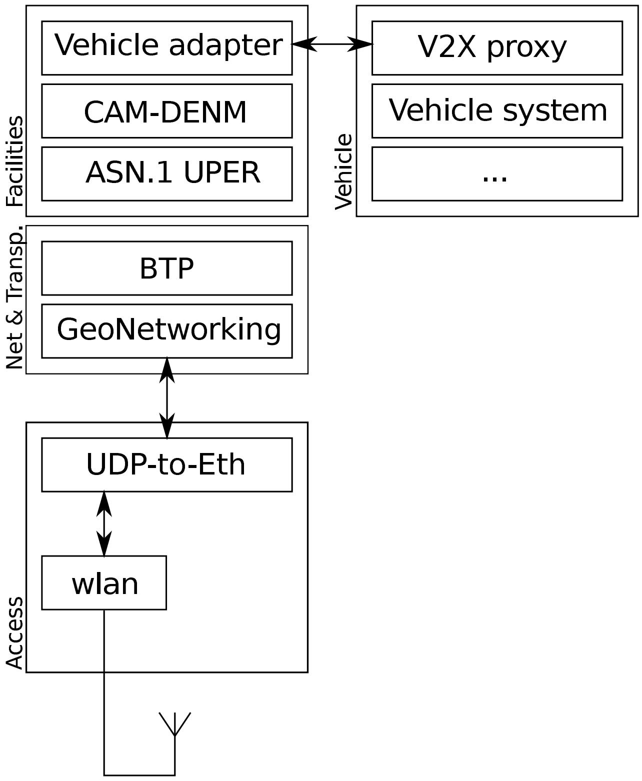


Figure 3.1: *This figure illustrates the schematics of the communication system. All data traffic inbound and outbound are communicated via UDPs concerning the GeoNetworking. The lowest layer will handle the outgoing and incoming data traffic (V2X) through a data link layer, between ethernet packets and UDPs. The communication stack will decode and encode the messages in the GeoNetworking stack. A basic direct implementation of GeoNetworking [11] is Vehicle adapter [12], which is piece of software developed and intended for Simulink framework controller system. The Vehicle adapter will passively listen for UDPs from the vehicle main controller system for constructing messages to send as well reversely listening for inbound messages from the vehicle environment.*

protocol, formally the networking protocol of vehicular ad-hoc network communication. This will enable complex network routing methods such as targeted GeoBroadcasting, and message forwarding etc.

Due to the encapsulated design of the communication system, the data are sent via UDP, between the vehicle controller system and the communication system. The payload will be of three different kinds: CAM, DENM or iCLCM whereas the first two are official standards of V2X. An internal protocol is defined for packing and unpacking the payload in UDP. A basic implementation built upon the GeoNetworking stack [11] is the Vehicle adapter [12]. It is completely developed in Java initially intended for a Simulink real-time framework controller system handling the data traffic in between.

Hardware and drivers The lower layer of communication will need to be facilitated on the same computer system where the wireless network card interface is installed. However, the GeoNetworking software may operate on a different separate machine since the communication is established via UDP. The computer is required to be compatible with the network card that is capable of operating on 5.9 GHz band. The developers of GeoNetworking communication stack suggest some hardware setup that may be operational with certain customized drivers [12] [11]: *alix boards*[1] and its successor *apu platform*[2], and *Hummingboards*[3].

The GeoNetworking stack is intended to operate according to ETSI ITS-G5 technology. There is some slight difference in the protocols of 802.11a and 802.11p in the MAC layer. In order to make the network card fully functional and compatible with ITS-G5 one needs to modify the network drivers properly thus patching

---

[1] `http://www.pcengines.ch/alix.htm`

[2] `http://www.pcengines.ch/apu.htm`

[3] `https://www.solid-run.com/freescale-imx6-family/hummingboard/`

Figure 3.2: *The Figure is taken of the hardware setup of the communication system. The computer is of model PC engines APU with wireless network card based on Atheros AR92xx. The antenna is from MobileMark of model ECOM9-5500 which operates on frequencies of 5-6 GHz and was measured to have a secure range up to* 200 m.

the Linux kernel. There are some modified Linux driver with ITS-G5 support available, ath5k[4] and ath9k[5] drivers modified by *Czech Technical University, Industrial Informatics Group* (Special thanks to Sojka M.[6]) and *Componentality.* For ath5k drivers, network cards based on Atheros AR5414 chipset are recommended. There is a complete list of compatible cards available[7]. While for ath9k drivers, Atheros AR92xx-based cards are recommended, likewise the complete list of compatible cards is available[8].

The antennas must as well abide the ITS-G5 specifications for wireless communication; they must be operational in the 5.9 GHz band. The broadcast range of the antenna may be an important factor when choosing a particular model on the market. There are different shapes available which may influence the placement of the antenna on the vehicle. One example of an antenna that fulfills the specifications of ITS-G5 is the *ECOM9-5500* from MobileMark[9]. It has a range of roughly 200 m and a magnet-mount to place it on the body of the vehicle.

Software Since the ITS-G5 technology is relatively new, drivers and support for hardware are scarce and limited. Still, there are modified Linux drivers (and Linux kernels) with a partial or even full support of ITS-G5. Generally for any operating system in order to run the GeoNetworking stack [12], one needs:

- a well defined and established connection to the vehicle main controller system for an example in the same local network area.
- drivers with ITS-G5 support in the operating system along with an operational network card and an antenna.
- a java runtime environment (JRE) to execute and run the GeoNetworking communication software stack.
- a data link layer for relaying Ethernet data packets from and to two different network interfaces.

---

[4] `https://wireless.wiki.kernel.org/en/users/drivers/ath5k`

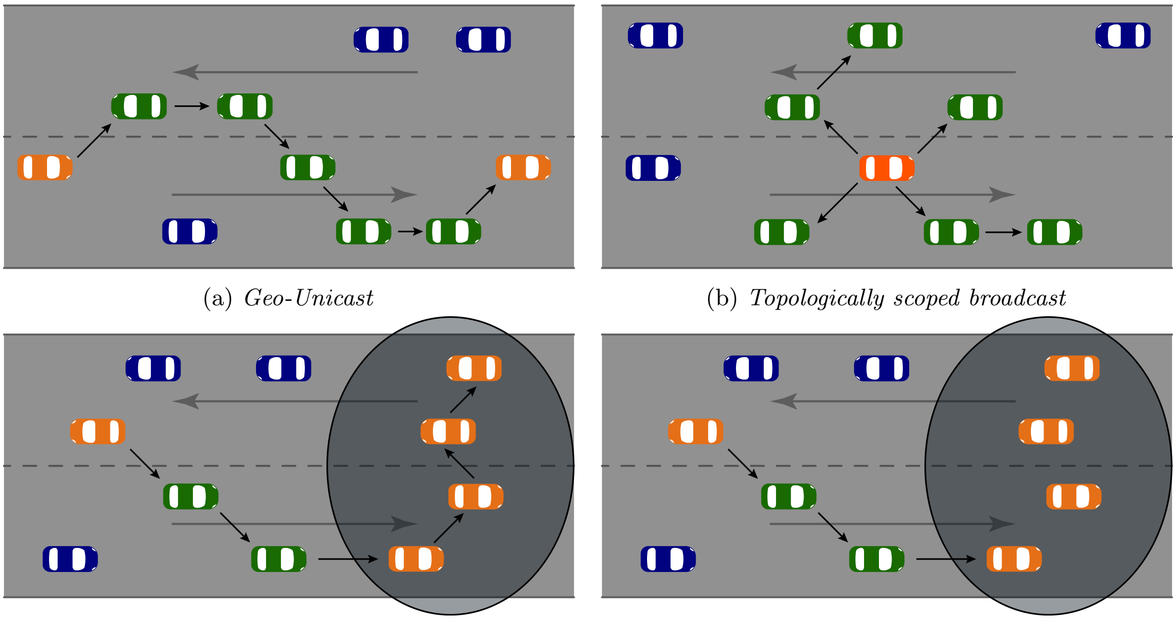
[5] `https://wireless.wiki.kernel.org/en/users/drivers/ath9k`

[6] sojkam1@fel.cvut.cz

[7] `https://wireless.wiki.kernel.org/en/users/drivers/ath5k#supported_devices`

[8] `https://wireless.wiki.kernel.org/en/users/drivers/ath9k/products`

[9] `https://www.mobilemark.com/product/magnet-mount-single-band-5000-6000-mhz-9-dbi-omni-directional-antenna-for-wifi-applications/`



(a) *Geo-Unicast* (b) *Topologically scoped broadcast*

(c) *Geo-Broadcast* (d) *Geo-Anycast*

Figure 3.3: *Different geographical forwarding (routing) features of the GeoNetworking protocol are shown in the Figure. The forwarding types are Geo-Unicast (point to point), topology scoped broadcast (point to multipoint), Geo-Broadcast, and Geo-Anycast. These types of routing may prove useful for a connectionless communication among large number vehicles in a certain area.*

Ideally one might want to have a real-time operating system which may be an option to implement. The real-time operating system runs applications which process data without any middle hand buffering which reduces the delay latency even further increasing consistency of the time it takes to process a task. By implementing this, it would increase the robustness of the system and decrease processing time in general.

GeoNetworking is a basic implementation of the ETSI ITS-G5 specifications and requirements [6][7], and the schematics of the communication system can be viewed in Figure 3.1. This piece of software was partially implemented of a group of people associated with the i-Game project and received funding from the European Union for its development while being an open project available as open source. The GeoNetworking software has the main role of maintaining the communication protocol among the intelligent vehicle systems. It is a network protocol for ad hoc wireless network routing exploiting the geographical positioning of the nodes for more efficient packet routing. This is called *geographical addressing* where the IP and the geographical location are embedded for example in the header part of the message. This allows multiple wireless hops among multiple surrounding vehicles or *road side units* (RSU) making message forwarding possible on a lower layer.

Generally, there are four types of geographical forwarding (routing) features in the GetNetworking protocol: Geo-Unicast (point to point), topologically scoped broadcast (point to multipoint), Geo-Broadcast, and Geo-Anycast. These different types are illustrated in Figure 3.3. GeoUnicast is a one to one connection between two nodes. The purpose of this message forwarding could be for example where one might want to communicate with the platoon leader in a scenario where they cannot establish a direct connection. Topological scoped broadcast is a type forwarding where the sender's broadcast is aided by the recipients, extending the broadcasting range even further. Lastly, Geo-Broadcast and Geo-Anycast are a type of forwarding where one have a target area where the broadcast specifically applies to. The difference between the two is that Geo-Broadcast requires the recipients in the targeted area to forward the message further while the other one does not. At current version of the software, there is no implementation of Geo-Broadcast, Geo-Unicast, Geo-Anycast.

GeoNetworking protocol utilizes the Basic Transport Protocol (BTP) where the packet structure is visualized in Figure 3.4. The design of BTP was to provide an end-to-end, connectionless data transfer service in ITS ad hoc networks in the network transport layer. The purpose is to multiplexing and demultiplexing of the incoming messages (CAM, DENM, and iCLCM) in an efficient way. This partially results in BTP being an arguably unreliable protocol, as the BTP packets may be lost och duplicated when broadcast.

MAC header	LLC header	GeoNetworking header	GeoNetworking security header (opt)	Payload (opt)

Figure 3.4: ***Basic Transport Protocol (BTP) packet structure*** *consists of five parts whereof the last two parts are optional fields. The MAC header contains the header of the MAC address of the sender while the logical link control (LLC) header contains the necessary information for the data link layer which to transfer the packet to intended layer. The GeoNetworking header consists of three fields: the basic header, the common header, and optionally an extended header. The common header provides the information of the packet type for the GeoNetworking protocol to differentiate between the types of incoming packets.*

The packet structure mainly consists of five parts, whereas the first three header fields are required by the protocol standard. It is important to note that BTP uses *big endian* as their byte order format convention. The three first headers specify important data combined for the protocol to be efficient. The specified fields are the MAC address of the sender, the logical link control header, and the GeoNetworking header. When the packet is received at the network layer, fast decisions can be made whether the payload is relevant or not to the recipient node thanks to BTP. Forwarding functionality is also specified in the BTP headers making it arguably efficient since it can differentiate the different types of incoming data packets at lower layers. The last two fields in the BTP packets are GeoNetworking security header and payload of the (CAM or DENM) messages whereas both of these headers are optional by the BTP. The security header provides the protocol the essential information for future implementations for communication security, message integrity, and confidentiality. At the current state of the software, there is no implementation of any security at all as the vehicular communication technology is relatively new.

For encoding and decoding message, GeoNetworking has implemented Abstract Syntax Notation One (ASN.1) Unaligned Packed Encoding Rules (UPER) accordingly with the ETSI standards for CAM [8] and DENM sets [9]. It specifically describes rules and structures for representation, transmitting, encoding, and decoding data values, and is commonly used in telecommunications and computer networking. Due to the formal nature of ASN.1, it is made possible to perform the data validation in most software tools if desired.

Formally, there are two message sets: *Cooperative Awareness Message* (CAM) [8] and *Decentralised Environment Notification Message* (DENM) [9] in cooperative intelligent transport systems (C-ITS) in European standards. There is also a custom made message set specially designed for intersection, platooning, and merging for GCDC purposes; that is *i-Game Cooperative Lane Change message* (iCLCM). All the message sets are abiding the common data dictionary design [10], which achieves a semantic interoperability among them. The implemented message sets may be seen in the overview in Table A.1. The table shows all message fields that are used in the 2016 GCDC. Specifically, in the i-Game event, it is required to broadcast iCLCM and CAM at 25 Hz where CAM is normally sent in a range of 1 Hz to 10 Hz depending on the traffic situation. The main reason to this is that during this event, it is crucial to have a high update frequency of the incoming data from V2V to achieve an automated vehicle with high cooperativeness in a safe manner.

CAM set is dedicated to conveying the basic information of the vehicles in V2V communication, such as their geographical positioning along with absolute heading, velocity, acceleration, vehicle role, and among much more. Safety applications may be built upon this type information, for example accurately calculating the collision estimation by using the broadcast vehicle position and dynamics. The CAM message structure consists of five parts which are illustrated in Figure 3.5. They are listed as ITS protocol data unit (PDU) header, basic container, high frequency (HF) container, low frequency (LF) container (optional), and respectively special vehicle container (optional). The ITS PDU header contains the protocol version as well the message type and the ITS-ID contains the ID of the originating ITS station. In the basic container, there more fundamental information about the originating ITS station. The highly dynamic data and the information are placed in the HF container such as position, motion dynamics of the vehicle and time stamps while the static information as vehicle dimensions are placed in the LF container. For a special vehicle such as heavy goods trucks, and public transport vehicle, the last container is used to provide additional information that could be useful for example specifying the type goods it is delivering in the trailer or number of passengers in the public transport vehicle.

DENM, on the other hand, is designed for V2I communication, handling the information regarding road hazard scenarios or abnormal traffic situations. The message header also contains information similarly to CAM, the information regarding the roadside unit (infrastructure ITS station) such as position and type of station. The general DENM message structure may be seen in Figure 3.6 which consists of five parts: ITS PDU

ITS PDU header	**Basic container**	**High frequency container**	**Low frequency container (opt)**	**Special vehicle container (opt)**
		Vehicle high frequency container	Vehicle low frequency container	Public transport container
		Other containers	Other containers (yet defined)	Public transport container
				...

Figure 3.5: *The message structure of cooperative awareness message is illustrated here. It is mainly composed of five parts: ITS protocol data unit (PDU) header, basic container, high-frequency container, low-frequency container, and special vehicle container whereas the last two are optional to include in the message. The ITS PDU header contains information of the protocol version as well the message type and the ITS-ID of the originating ITS station. Similarly, the basic container includes more detailed basic information regarding the originating ITS station. The more dynamic information, such as position, motion dynamics, and time stamp, are located in the high-frequency container. While the static information, such as vehicle dimensions, are located in the low-frequency container. The last field special vehicle container includes the information specifically related that vehicle, for example for information of which type of heavy truck or their transportation load, or the public transport's number of passengers.*

ITS PDU header	**Management container**	**Situation container (opt)**	**Location container (opt)**	**À la carte container (opt)**

Figure 3.6: *Decentralized environmental notification message (DENM) structure is shown here. It consists of five parts with first part as the ITS PDU header and rest as containers which constitutes as the payload of DENM. Like CAM, ITS PDU header contains the important information about the message, such as protocol version, message type and location of the originating ITS station. DENM management and protocol information are in the mandatory management container. The other three containers are meanwhile optional to include in the DENM message. The situation container contains the information regarding the type of detected event or situation. The location container holds the information related to that event location, the area of effective and location of referencing. The last container, à la carte container, shall contain the additional information that is considered relevant to the event or situation that does not fall into the previous containers.*

header, management container, situation container, location container, and à la carte container whereas the last three are optional. DENM shares the same kind header part as the CAM while the other four containers make up the payload of the DENM. The mandatory management container contains the information related to the management protocol of DENM. The situation container has the information of the type of event or situation it wants to inform about. The location container is straightforward a container holding the location of the affected area and related information. While à la carte container has all additional information regarding the event or situation that does not fall into the previous container that is still deemed to be important information to convey.

In order to achieve highly cooperative automated driving vehicle, iCLCM set was created to extend the previous two message sets. Since iCLCM is not a standard anywhere, the documents of specifications and requirements are detailed in i-Game's proposal document of deliverables to the European commission [13]. The message structure is very similar to the two previous message sets which is detailed in Figure 3.7. Like the structure of the previous types of messages, iCLCM also has got an ITS PDU header containing the information about the message type, station ID of the originating ITS station and protocol version. The next iCLCM header basically contains the generated timestamp of when the message was created. HF and LF containers are designed in the same fashion as CAM, holding the highly dynamic and static information respectively. MIO container has got specific information, such as position and motion dynamics, of objects surrounding the vehicle. Lane, pair ID and merge container hold information about the current lane, the paired up partner vehicle and all relevant information that is needed in order to perform merging scenario respectively. The S container has got the additional information details that are needed for the i-Game project

ITS PDU header	iCLCM header	HF container	LF container	MIO	Lane	Pair ID	Merge	S

Figure 3.7: *The figure shows the message structure of i-Game Cooperative Lane Change message (iCLCM) set. Similarly the previous two standard sets, it has got an ITS PDU header containing the information of message type and ITS station ID while the iCLCM header holds the generation time stamp of the message. The HF container has got the high dynamic data of the vehicle while LF container has the static data. Most important object (MIO) container holds the information, such as distance, distance derivative, and heading angle of the objects around the vehicle. Lane container simply states what lane you are in, while pair ID container is simply the station ID of your pairing partner. The merge container has got all relevant information in order to perform a platoon merging. The S container holds the additional information that does not fall in the previous container that is needed for the specific scenarios within i-Game project.*

that does not fall into the previous containers.

The implementation of GeoNetworking requires a separate data link layer entity in order to be fully functional. It is a protocol layer that transfers information from near adjacent wide area networks, local area networks, between nodes, and specifically in this case between network card interfaces. There are generally two sub-layers within the data link layer: media access control (MAC) and logical link control (LLC) which are well defined and available in BTP. These layers will ensure that an initial connection has been correctly and successfully set up and slicing up data into data frames while handling the handshakes from the receiver when packets have been successfully delivered. Within this layer, it is also possible to detect possible packet corruption and even correct errors that may exist in the physical layer.

GeoNetworking is implemented in such a way that it is sending and receiving UDP from the data link layer software on certain ports for outer communication (V2X). These BTP packets contain MAC- and LLC headers which will allow the data linker to create Ethernet frames which will be forwarded to the network interfaces. The developers of GeoNetworking recommend using one of the two existing data linkers that they have developed and provided, udp2eth[10] and utoepy[11]. Both of them provide identical functionalities but are developed in different languages (C and python).

The GeoNetworking is a separate independent system and needs an interface to communicate with the vehicle system. Severinsson A. created Vehicle adapter for this purpose [12]. It is a Java application built upon the GeoNetworking library. The interface is mainly developed towards a Simulink system but is constructed in such general way to work with other systems as well, using UDP networking as a communication base. The communication protocol for packing and unpacking of purpose to construct CAM, DENM and iCLCM can be seen in Tables A.2, A.3 and respectively A.4.

3.2 Research questions and evaluation methods

This thesis investigates and evaluates the proposed the state of art of vehicle communication (V2X) for real world scenarios which are featured and demonstrated in the i-Game project's 2016 GCDC. The functionalities of vehicle communication are demonstrated explicitly in three different scenarios: EV-, intersection-, and merging scenarios. The research question is posed as *Is it feasible to use V2V communication in a real-world emergency situation, traffic intersection, or highway merging scenario?.* The goal of this thesis is to provide new interesting pieces of information, observations, and results that may contribute the research as well the development of V2X communication. By observing the performances of the vehicle communication in each heat in 2016 GCDC, it will provide some unique results for the future development of vehicular communication. At the same time discovering flaws in current solution which could not be foreseen during implementation. Experiences and opinions regarding deploying the vehicular communication solutions will be obtained by interviewing the competitors of 2016 GCDC. Furthermore, evaluations regarding the time response (latency) and data & channel congestion (throughput) of the V2V systems will be conducted independent of 2016 GCDC and presented in this thesis.

---

[10] `https://github.com/jandejongh/udp2eth`

[11] `https://github.com/alexvoronov/utoepy`

Evaluating the time response
The most intuitive way to evaluate time response is to measure the time point when the BTP packet being transmitted via the lower physical layers to the point of the message finished being encoded/decoded at the upper application layer. For this evaluation, the measurements will be conducted explicitly in the data linker and in the vehicle adapter. The time points will be when the packets are received and to the point where they are forwarded to next layer or system.

This will provide critical information regarding the vehicular communication system's performance in real time. This heavily affects the consistency of the performance which is crucial when speaking of real-time systems. Ensuring that the transmitting data is fresh is arguably essential when it comes to robotic systems especially self-driving vehicles.

Evaluating the data and channel congestion
Data and channel congestion may be evaluated by finding the maximum rate of the system can process and parse the messages forward. Beyond this rate would cause the system to queue the messages and a congestion would be present. This limitation will most likely depend on three bottlenecks: the transfer rate in the physical and the lower layers, the software implementation of the systems and the processing power of the hardware components. There may be several ways to stress the system, either through output or input of data or even a combination of both.

For this thesis, we will take a look at the instantaneous throughput frequency and the average throughput frequency. The instantaneous throughput frequency may be evaluated as

$$f_{instant} = \frac{1}{t_{i+1} - t_i} \tag{3.1}$$

where t_i is the time stamp of the processed message i. The average throughput frequency is straightforward computed as

$$f_{average} = \frac{N_{message}}{T_{duration}} \tag{3.2}$$

where $N_{message}$ is the number of message processed during the time $T_{duration}$. The measurements will be taking place in the application layer.

Interview questions The material from the interviews with the competitors will be based on the following questions:

- What solution the teams deploy for V2V during GCDC?
- What challenges did the teams encounter regarding the solution?
- What benchmark performance regarding real-time response and message congestion?
- What can be improved and re-evaluated in respect to V2V technology and currently deployed solution?

The answers are either gathered at the competition or via email responses.

4 Results

In this section, the technical results regarding the time response and the throughput of the data linker and vehicle adapter will be presented first. Secondly, the interview material gathered from the competitors of 2016 GCDC regarding working with the vehicular communication presented. Not all competitors were interviewed for this thesis.

4.1 Time response

The measured time durations from the point of receiving the message to the point of forwarding the processed packet to the next layer were collected. The data is normalized and put in distributions for the different cases of outgoing and incoming message traffic for the data linker and vehicle adapter. This may be seen in Figure

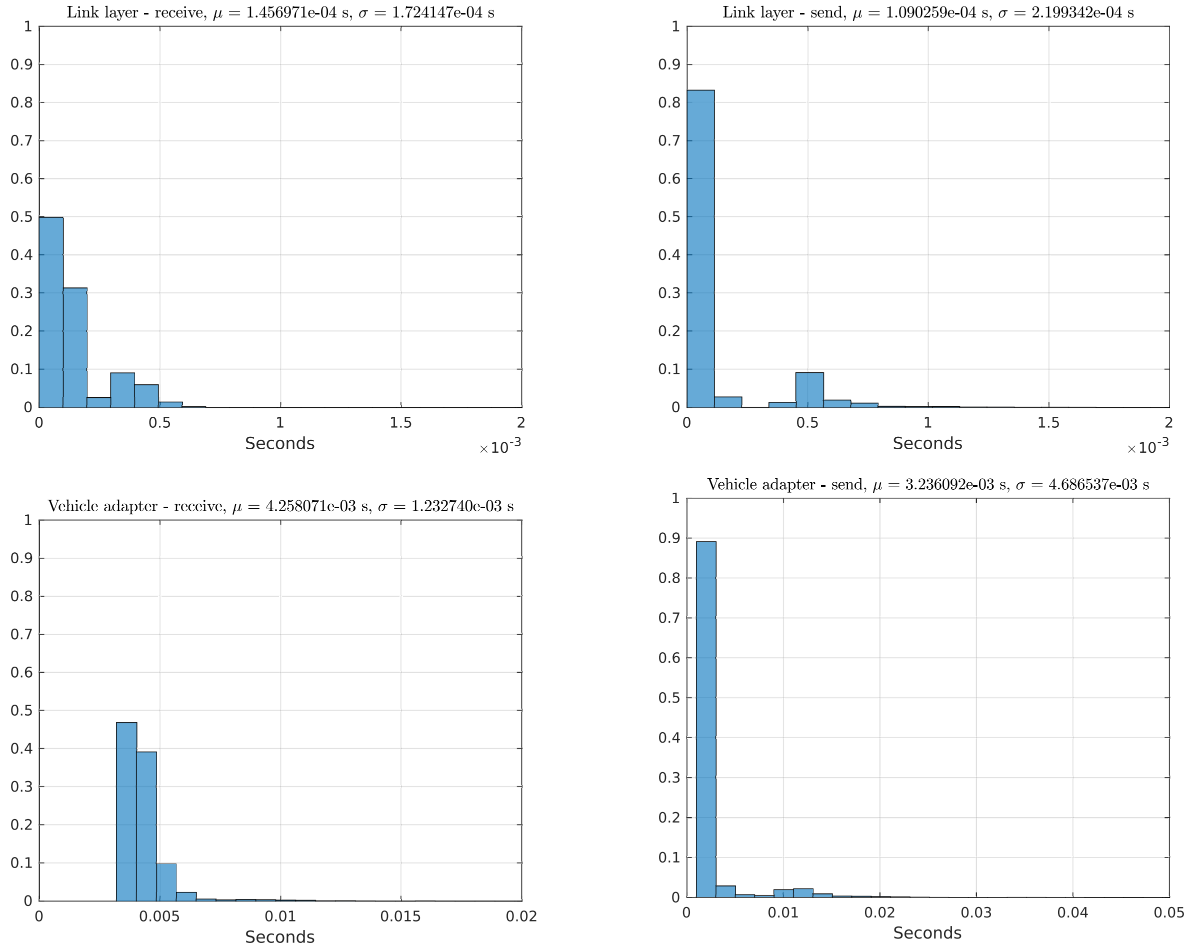


Figure 4.1: *Histograms of the time distribution of the time duration to process and packet information in the higher application layer, Vehicle adapter, and the lower data link layer are shown in the figure, both sending and receiving cases. Notice the time scale difference of the data link layer and the vehicle adapter as they differ by a factor of 10. The tests completely separated, meaning the test are cases are only either receiving or sending, and not a combination of both. There is a lower latency in the lower layer, roughly around* 0.000 146 s *and* 0.000 109 s *for receiving respectively sending test cases compared to the Vehicle adapter case, approximately* 0.004 26 s *respectively* 0.003 24 s*. Assuming that the data transfer time between the layers is negligible, then the expected latency of the vehicular communication system is less than* 0.005 s.

4.1. In the lower data link layer, there is a lower latency, e.g. more rapid responses with the expected values of 0.000 146 s and 0.000 109 s for receiving respectively sending packets. In contrast to the higher latency in the vehicle adapter where the expected values are 0.004 26 s respectively 0.003 24 s. It is mildly expected to have a higher latency in the higher layers. The comparison is roughly a factor of 10. Assuming that the data transfer time between the layers is negligible, then the expected latency of the vehicular communication system is less than 0.005 s.

4.2 Throughput

The instantaneous frequency over time and throughput distributions are shown in Figure 4.2 and Table 4.1. The measurements are done in the same layers as the system controllers which are located in the application layer. The data flow and stress were simulated at the rate of 10, 100 and 1000 messages per second and executed on the same operating system performing the measurements. 10 Hz is a reference case test which would correspond the data flow or throughput from a single vehicle system. The results produced for this case is very close to the ideal performance.

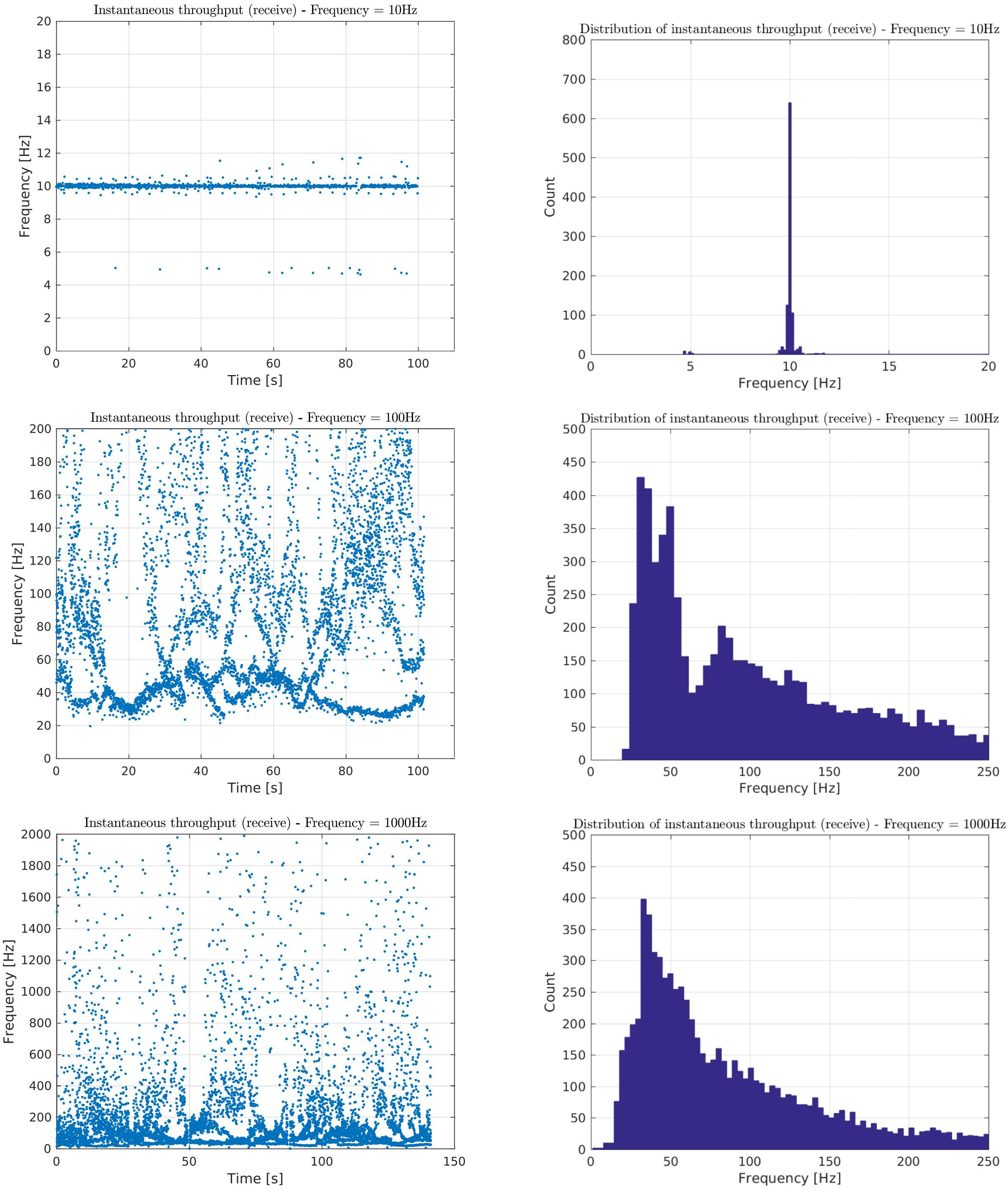


Figure 4.2: *The figure shows the throughput of the rates of 10, 100 and 1000 messages per second in time series (instantaneous frequency) and frequency distributions. The measurements were made in the application layer on the same operating system simulating the data flow and stress. The lowest frequency at* 10 Hz *serves as a reference, which would correspond roughly the data traffic of one vehicle. Both of the diagrams look as expected with little signs of anomalies in the frequency. This is close to the ideal case of throughput. The other two cases of* 100 Hz *and* 1000 Hz *show symptoms of stress and deviation from the ideal case of throughput at the same frequency as being sent. The statistics of the mean-, median-, and standard deviation values may be seen in Table 4.1.*

Table 4.1: The table shows the statistics of the instantaneous frequency and the average frequency over time for different message frequencies.

Message freq.	Average inst. freq.	Median inst. freq.	Standard dev.	Average freq.
10	90.23	10.00	892.36	10.01
100	5656.05	151.35	21214.36	98.41
1000	3359.92	94.80	20081.83	70.87

While the other cases of 100 Hz and 1000 Hz show anomalies and a large deviation from the ideal case of performance and consistency. This can objectively be seen in their standard deviations as well in their time series diagrams. Furthermore, there seems to be a slowdown in the higher frequency since the average frequency seemingly decreased as the message frequency got higher.

4.3 Responses from the competitors

The interview material was collected both during and after competition through personal interviews and email responses.

Universidad de Alcalá (UAH), Spain
The Spanish team deployed the solution that the organizers proposed, both hardware and software. They did not make use of the Vehicle Adapter. In their expressed opinion, the currently proposed V2V solution might not the most optimal way to communicate with vehicles. They also expressed some difficulties in establishing communication in certain areas due to large obstacles such as bridges, tunnels, large vehicles, and even cars. This would prevent them from being able to fully communicate with other teams this limiting their ability to cooperate. Another problem is the range of the communication. At the most optimum settings, they could establish a reliable communication at 150 m at the most which they considered too short and this range is even shorter in worse settings. They proposed that there should be beacons or vehicles that should have the capabilities to forward messages thus extending the length of reach of the messages in V2X which is not currently implemented in GeoNetworking.

The Spanish team had not formally conducted tests or benchmarked the V2V system but speculated there risk of overloading the vehicle system with data messages from the vehicular communication system. Hence they suggested that one should re-evaluate the rate the messages are sent per vehicle. Additionally, they commented that increasing the message frequency does not always result in a better performance due the fact messages are not guaranteed to be processed by the others. They would like to have the chosen frequency band of V2X re-evaluated as well reconsider other frequencies to put V2X communication on.

Université de technologie de Compiègne (Heudiasyc laboratory), France
In contrast to other teams, the french had their own vehicular communication solution. The hardware was given to them by a colleague of theirs, which was a product manufactured by an American manufacturer. But due to a message protocol conflict between the American and European standards of V2V communication protocol, ultimately lead to incompatible data exchange in the vehicular communication. For these reasons, they had to develop their own software to encode and decode V2V messages properly with the regards to the European standards.

They also share a critical standpoint on the V2X aspect as one are allowing other to influence your vehicle's action. This could pose many problems due to hacking, spoofing, or just malfunctioning sensors of other vehicles that are broadcasting defective information. This calls for more information theory to be required and furthermore further implementation of sensor fusion that confirms incoming V2V information.

As vehicular technology stands right now, there is no communication security or integrity of the messages which might be a problem according to them. "Whom do we trust enough to receive information through vehicle communication? One natural response to the problem is to let the government handle infrastructure communication but people might be reluctant to spend money on such things." - paraphrasing the french team's response.

KIT Karlsruhe, Germany
With experienced from last competition, 2011 GCDC, they decided to use the open source Java stack pro-

posed by the GCDC organizers combined with the hardware: Compex WLE200NX wifi card with an ASRock Q1900DC-ITX mainboard. They created a ROS node that interfaces to the communication stack via UDP. The most important for them was that the solution enabled them to decode and read the messages from V2V reliably, but they did not formally perform any test to confirm this. Furthermore, they found that the open source solution GeoNetworking was easy to use and fulfilled their demands and didn't contain any major bugs or glitches. With the help of the organizers and other teams, many minor bugs were found quickly and addressed accordingly. They also speculate additional message types could be necessary depending on what one need to do in different scenarios for the future development of V2V.

Chalmers University of Technology (Car team), Sweden
Chalmers car team, specifically Severinsson A., developed another layer on top of Geonetworking stack called Vehicle adapter [12]. Via UDP messages the vehicle main controller is able to send V2V messages to the Geonetworking stack through the vehicle adapter. This is published as open source software thus inviting further research and development of ITS-G5. But the development of this was a difficult task not to mention setting up the modified drivers and userspace modifications in order to run software properly. The Vehicle adapter was tested in several aspects: throughput, response time and interoperability. It was benchmarked to handle roughly 500 messages per second while having a latency delay of 10 milliseconds. It was also plug in compatible with a Kapsch modem to check it's interoperability with other solutions.

5 Discussions

In this chapter, the findings will be further examined, interpreted and as well evaluated. Further discussions how to improve the results and the vehicular communication technology will be expressed as well. As the vehicular communication becomes a viable technology for a vehicle standard, this would open up for more applications as well more research areas such vehicle communication security and message encryption. More importantly, it would open up for more complex and cooperative behavior that could increase the fuel efficiency even possibly be part of the solutions to the traffic congestion.

5.1 Latency

Communication latency should be as low as possible to ensure the freshness of the data as it is being transmitted. For the 2016 GCDC, there were formal requirements and specifications of V2V latency. It is stated as in the communication requirements: "All vehicles shall ensure a maximum communication delay of 100 ms.", which is referring to the latency from the reception of the packet to the point of processing it in the vehicle controller. The findings in the reports suggest the latency should be in the order of 5 ms which is below the required latency with a good margin.

There is a possibility that this requirement will be changed to an even lower latency in the near future to ensure the freshness of the sent data packets. This is especially true regarding platooning and other cooperative behavior that requires even more precise and accurate data. So improving the latency may become relevant in the future development of autonomous vehicles who utilize V2V communication. As mentioned earlier, by introducing a real-time kernel (real time operating system) for V2V communication could reduce the latency and as well improve the consistency since this would get rid of middle-hand storage and data buffer that are being passed through different layers.

5.2 Throughput

The presented results for this thesis show some noteworthy remarks. In the measurements especially for the two high message frequencies, one can see a high standard deviation in comparison to the 10 Hz test case. Another remark is that it seems like the throughput decreased as the message frequency got higher. With other words, it looks like the stress decreased the processing capabilities (when compare the average frequencies of 98.41 Hz respective 70.87 Hz. The likely culprit of this is the measurement setup, which would most likely give rise the just mentioned symptoms. The measurements and the simulated data flow were operated and managed by the same computer system. This would most likely cause the problems in the measurements. An improvement to this would be to separate the measurement and the data flow generation to different distinct computer systems.

However, a rough and somewhat pessimistic estimation of the maximum throughput of the current technical specifications should be around a couple of hundred messages per seconds. The estimation is based on that one has roughly 6 Mbps of the raw transfer rate in the channel. One can estimate that 50 percent is utilization for V2V communication. Let us assume that a message is approximately 3000 bits for transmission data. This would give us several hundred messages per second for transmission, in both sending and receiving simultaneously. As for an ad hoc mobile network, this would correspond to roughly twelve vehicles assuming they are operating with 75 Hz message frequency in the case of the scenarios of 2016 GCDC.[1]

Outside of the 2016 GCDC, the throughput at the rate of 700 messages per second would correspond to roughly 70 to 700 C-ITS vehicles (at the rate of 1 Hz to 10 Hz). This capacity is reasonably acceptable but could pose a problem in major cities or traffic congestion in open spaces whereas the messages are forwarded and not essentially bound by the broadcast range of the origin.

5.3 Vehicle communication performance

Many vehicle systems were able to communicate each other using their own solutions of choice. The majority of the teams chose to use the solutions proposed by the organizers, both the hardware and the open source Geonetworking stack along with the Vehicle Adapter. There was a team struggling with encoding the message correctly which resulted not being able to broadcast their messages properly due to the mismatch in the protocol standards in Europe respectively the United States. However, they managed to alter the software to decode the incoming messages so they were at least capable of reading the messages from other teams.

A minority, exclusively those who chose the Vehicle Adapter solution, had a problem of receiving DENM messages from the RSU:s by the organizers of 2016 GCDC. Through several investigations and testings, found no problems in receiving the actual message but it seemingly never came through the decoding phase. It is suspected that the organizers had a mismatch in their broadcasting location information in their BTP header, pointing to a location far away which made the message ambiguous thus was discarded by the software automatically. This was bypassed through disabling the header check in the software in the Geonetworking stack but problem was never resolved during competition.

Many teams experienced problems in establishing reliable communication due to a dynamic environment, obstacles and even the participating vehicle (specifically the trucks due to their vehicle size) were interrupting the vehicle communication signals. There was no real permanent solution to this problem either. The symptoms were eased by rearranging the order of the participating vehicles or changing the scenario location.

5.4 World wide standards

It did not take a long time until the teams in 2016 GCDC noticed that there was a mismatch in one of the team's message standards which resulted in communication failure. This is clearly an example of when there are independent communication systems that are not using the same standards for communication. For this specific case, the affected team was using an American standard for message encoding and decoding. Furthermore, the United states are not the only nation that has enforced its own V2V standards; Japan also developed its own standard for V2V communication which operates completely different frequency band namely 700 MHz [14]. This different band gives this technology completely different conditions to work with. For example, due to its low frequency, it will give more reliable, not to mention less noisy transmissions over longer distances. However, for the same reason, it is only capable transmitting data packets at a lower transmission rate.

Clearly, for vehicular communication across nations on an international level, a worldwide standard should be formalized and agreed upon. This is however easier said than done since the frequency bands are essentially different from nations to nations which will complicate the process of allocating a specific band for ITS purposes. There are other ways to deal with this problem, for example, the WiFi technology does not have a worldwide standardized coherent frequency band. This is solved by having compatibility implemented both hardware- and software-wise in the WiFi products. As a consumer, one needs to configure the product accordingly where the product is used. This is a similar case for today's cellphones for same reasons mentioned earlier and is

---

[1] Further discussion is available: https://github.com/alexvoronov/geonetworking/issues/13

solved in a similar fashion. This could be the case of dealing the problem of not having a worldwide standard of vehicle communication.

5.5 Applications

Traffic congestion is common phenomenon around the world as urbanization is happening both in western- and developing nations since this is a necessity to achieve high growth and strong economy [15]. Rapid urbanization may pose future problems such as poor infrastructural planning as well road and highway architecture which may contribute to the traffic congestion phenomenon. But little things as sudden braking from one individual driver may cause a major phantom congestion or bottlenecks on highways [16]. These kinds of phenomenon are in fact that periodic and common which has resulted in becoming a part of peoples' daily life. This has negative effects ranging from individual level (for example, commuting time and psychological health) to a global level (for example, fuel consumption, road fatalities and sustainability).

A contribution to a possible solution to is cooperative adaptive cruise control which is an enhancement of today's adaptive cruise control. This new technology makes use of V2V communication and integrates and compliments the functionality of cruise control thus an advanced cooperative behavior. This has been studied through theoretical models and is showing promising results that may mitigate the impact and the effects phantom congestion [17]. Through cooperation among intelligent vehicles, it possible to synchronize the acceleration and deceleration with respect to the vehicles in the front and from the behind which counteracts congestion creation.

Platooning technology would greatly benefit from V2V technology as demonstrated in 2016 GCDC platoon merging. By synchronizing the acceleration and braking of the vehicles, the intermediate distance between the vehicles can be reduced thus reducing the air drag. Platooning would also increase the drivers' (followers) convenience since platooning may not require their full attention. Some estimate that fuel consumption could potentially be reduced by 20 percent as well the road fatalities by 10 percent [18].

6 Conclusions

The development of autonomous vehicles is taking place in a rapid pace both in the industries and academia. The vehicle systems are becoming more refined and sophisticated than ever and are already being introduced to today's market. As the technology advances towards to a driver-less solution, data gathering plays an important role in developing such systems. Vehicular communication is one way of conveying information to the surrounding intelligent systems and vice versa.

This thesis analyses the performance of one particular solution, open source GeoNetworking: Vehicle adapter [11][12] that abides and implements ETSI specifications and regulations regarding vehicular communication which is proposed within Europe. The open source solution is also demonstrated in an i-Game project, namely 2016 GCDC, in particular, three scenarios with different purposes of V2X communication. Some comments from the participating teams regarding the deployed software of the communication stack were gathered in this thesis. Two formal tests were conducted to further investigate the latency and throughput of GeoNetworking protocol. The results showed that the latency is less than 0.005 s if neglecting the data transfer time between the layers. This complies with the formal requirement that the latency of V2X communication system should not surpass 100 ms. However, improvements and optimization could come into question in near future in order to achieve more complex cooperative behavior that requires fresher data from its collaborators. The throughput benchmarked in our investigation at 98.41 messages per second at ideal settings. But the results of throughput in this thesis argues for the conduct of measuring may be greatly improved. The throughput results may be compared to the benchmark of 2016 GCDC whereas messages were exchanged roughly calculated at the best on a rate of 700 messages per second. This would correspond to a V2X communication network of roughly 70 to 700 C-ITS nodes which is a reasonably acceptable number of network nodes in most areas and scenarios.

The main purpose of the i-Game's project: 2016 GCDC was to demonstrate the advantages of vehicular communication in three different scenarios; emergency-, intersection-, and platoon merging scenarios. This gives rise to a unique opportunity to gather information from the participating teams regarding their vehicular communication solution and their thoughts and experience working with it. Many of the teams used and deployed the open source GeoNetworking library to their vehicle system successfully. This was done by either implementing their own interface upon the GeoNetworking stack or using the existing Vehicle adapter. Many teams expressed concerns about the current stage of vehicular communications on the subjects of information theory, communication security and integrity, and environment limitations on the physically transmitted signals. During the event, it was clearly that a common ground in frequency bands and protocols for the vehicular communication is essential or the communication would be less effective. On a worldwide level, this is not an easy issue to solve which may be seen in cases of the cellphone- and WiFi frequency bands where they differ from countries to countries.

Despite the mentioned concerns, the vehicular communications show significant promises and contributions to new types of applications in cooperative behaviors for autonomous vehicles. Platooning would greatly benefit from V2V as it is demonstrated in 2016 GCDC and could become an important factor in counteracting traffic congestion. From a sustainability perspective, platooning empowered by V2V could possibly reduce the fuel consumption significantly.

6.1 Future work

Vehicular communication is far from being complete and more development and research are needed especially in communication security. As the development of the autonomous vehicles is progressing, many of the vehicle's actuators are electronically controlled. Having a wireless communication channel open puts the vehicle controller system on a vulnerable position of cyber attacks with possibly deadly consequences with immense negative impact on autonomous vehicle reputation. Thus the security aspect of the vehicular communication must be in the consideration due to the fact this must be developed on a proactive basis rather than reactive basis.

V2X is no different from being an additional external sensor for the vehicle system. Receiving inaccurate information even spoofed data packets could have serious consequences for the autonomous vehicle's behavior. Authenticating the incoming messages and checking the integrity of the messages are ways of ensuring that the messages are truly sincere. But also a way of verifying the sender as a trustworthy broadcaster could come to question since cooperative behaviors are heavily dependent of trusting other parties.

As some teams in 2016 GCDC pointed out that the communication signals are heavily influenced and limited by the surroundings of the vehicles affecting the range of broadcasting and susceptibility to noise. This could be potentially be solved applying dual band technology to vehicular communication [19]. By combining usage of both low and high-frequency bands, the communication system could capitalize on the advantages of each the distinct band. Lower frequency signal has a better range, signal penetration and resistance to noise while high frequency allows faster data transmission. For example in CAM, there are fields in the message protocol that categorized in the low-frequency container. This could, for example, be put in the lower frequency band broadcast while the high-frequency data fields are broadcast on the higher frequency band. Developing this further could potentially increasing the efficiency of the data transmission thus relieving the throughput stress on the communication system.

References

[1] Institute of Electrical and Electronics Engineers. *Look Ma, No Hands!* Ed. by www.ieee.org. [Online; retrieved 13-February-2016]. Sept. 2012. URL: `http://www.ieee.org/about/news/2012/5september_2_2012.html`.

[2] S. Al-Sultan et al. A comprehensive survey on vehicular Ad Hoc network. *Journal of network and computer applications* **37** (2014), pp. 380–392.

[3] J. Harding et al. *Vehicle-to-vehicle communications: Readiness of V2V technology for application.* Tech. rep. 2014.

[4] S. Andrews and M. Cops. *Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary-Vehicle.* Tech. rep. 2009.

[5] B. T. Sharef, R. A. Alsaqour, and M. Ismail. Vehicular communication ad hoc routing protocols: A survey. *Journal of network and computer applications* **40** (2014), pp. 363–396.

[6] E. ETSI. 302 636-4-1 V1. 2.1-Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 6: Internet Integration; Sub-part 1: Transmission of IPv6 Packets over GeoNetworking Protocols. *ETSI, June* (2014).

[7] E. ETSI. 302 636-5-1 V1. 2.1-Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol. *ETSI, Okt* (2013).

[8] E. ETSI. 302 637-2 V1. 3.1-Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service. *ETSI, Sept* (2014).

[9] E. ETSI. 302 637-3 V1. 2.1-Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service. *ETSI, Sept* (2014).

[10] T. ETSI. 102 894-2 V1. 2.1-Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary. *ETSI, Sept* (2014).

[11] A. Voronov et al. *Implementation of ETSI ITS G5 GeoNetworking stack, in Java: CAM-DENM / ASN.1 PER / BTP / GeoNetworking.* June 2016. DOI: `10.5281/zenodo.55650`. URL: `http://dx.doi.org/10.5281/zenodo.55650`.

[12] A. Voronov, Zeverin, and D. Heuven. *geonetworking: Vehicle Adapter.* May 2016. DOI: `10.5281/zenodo.51295`. URL: `http://dx.doi.org/10.5281/zenodo.51295`.

[13] J. van de Sluis et al. DEL i-GAME D3.2 Proposal for extended message set for supervised automated driving. *EUROPEAN COMMISSION, SEVENTH FRAMEWORK PROGRAMME, Sept* (2015).

[14] A. of Radio Industries and E. Businesses. ENGLISH TRANSLATION: 700 MHz BAND INTELLIGENT TRANSPORT SYSTEMS, ARIB STANDARD. *Association of Radio Industries and Businesses, Feb* (2012).

[15] P. C. Annez and R. M. Buckley. Urbanization and growth: Setting the context. *Urbanization and growth* **1** (2009), pp. 1–45.

[16] D. C. Gazis and R. Herman. The moving and "phantom" bottlenecks. *Transportation Science* **26**.3 (1992), pp. 223–229.

[17] S. Calvert, T. A. Van Den Broek, and M. Van Noort. "Modelling cooperative driving in congestion shockwaves on a freeway network". *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC).* IEEE. 2011, pp. 614–619.

[18] T. Robinson, E. Chan, and E. Coelingh. "Operating platoons on public motorways: An introduction to the sartre platooning programme". *17th world congress on intelligent transport systems.* Vol. 1. 2010, p. 12.

[19] Y. Yamao and K. Minato. "Vehicle-roadside-vehicle relay communication network employing multiple frequencies and routing function". *2009 6th International Symposium on Wireless Communication Systems.* IEEE. 2009, pp. 413–417.

Appendices

A Vehicle adapter - Interface

Further details about the message fields that were used in the vehicular communication in the 2016 GCDC are be presented in here. All the message fields in CAM, DENM and iCLCM are listed in the Table A.1 as well their update frequencies and byte lengths. This table is a part of the deliverables of the GCDC organizers. Some message fields are custom made, tweaked and tailored for the GCDC event and are not a part of the European vehicle communication standards but rather in their own message set: iCLCM. It is important to notice that the messages are packed in a big endian order. The exact details and definition of each message fields may be found in the ETSI documents of CAM [8], DENM [9], and for the iCLCM in the deliverables 3.2 of 2016 GCDC documents.

The vehicle adapter is built on top of GeoNetworking communication stack which serves as an interface to the main vehicle system. The java software establishes the communication through UDP and the packet protocols are defined according to the Tables A.2, A.3, and A.4. The byte length and the order of message fields are especially important when unpacking and packing the UDP messages to the vehicle adapter. The ports for sending and receiving the UDP may be configured in the software as well some other additional configurations.

Table A.1: This table shows a list of used message fields in the i-game's 2016 project GCDC.

ID	Message field	Message set	Frequency	Bytes	Notes
1	Header	CAM/DENM/iCLCM	-	1	=2/1/10
2	GenerationDeltaTime	CAM	25Hz	4	-
3	Station ID	CAM/DENM/iCLCM	25Hz	4	Unique
4	Station Type	CAM	25Hz	4	-
5	Vehicle Role	CAM	1Hz	4	-
6	Vehicle length	CAM	25Hz	4	-
7	Vehicle rear axle location	iCLCM	25Hz	4	-
8	Vehicle width	CAM	25Hz	4	-
9	Controller type	iCLCM	25Hz	4	-
10	Vehicle response time constant	iCLCM	25Hz	4	-
11	Vehicle response time delay	iCLCM	25Hz	4	-
12	ReferencePosition (latitude, longitude, confidence)	CAM	25Hz	4	-
13	Heading (Heading, confidence)	CAM	25Hz	4	-
14	Speed	CAM	25Hz	4	-
15	YawRate	CAM	25Hz	4	-
16	Longitudinal vehicle acceleration	CAM	25Hz	4	-
17	Desired longitudinal vehicle acceleration	iCLCM	25Hz	4	-
18	MIO ID (measured by object vehicle)	iCLCM	25Hz	4	-
19	MIO range (measured by object vehicle)	iCLCM	25Hz	4	-
20	MIO bearing (measured by object vehicle)	iCLCM	25Hz	4	-
21	MIO range rate (measured by object vehicle)	iCLCM	25Hz	4	-
22	Time headway	iCLCM	25Hz	4	-
23	Cruise speed	iCLCM	25Hz	4	-
24	Merge request flag	iCLCM	1Hz	4	-
25	Safe-to-merge (STOM) flag	iCLCM	1Hz	4	-
26	Merging flag	iCLCM	1Hz	4	-
27	ID of fwd pair partner	iCLCM	1Hz	4	-
28	ID of bwd pair partner	iCLCM	1Hz	4	-
29	Tail vehicle flag	iCLCM	1Hz	4	-
30	Head vehicle flag	iCLCM	1Hz	4	-
31	Platoon ID	iCLCM	1Hz	4	-
32	Travelled distance inside the CZ	iCLCM	25Hz	4	-
33	Intention (left, right, or straight)	iCLCM	1Hz	4	-
34	Lane on which the vehicle enters the CZ	iCLCM	1Hz	4	-
35	Intersection vehicle counter	iCLCM	1Hz	4	-
36	Pair acknowledge flag	iCLCM	1Hz	4	-
37	Reference Time	DENM	10Hz	4	-
38	EventType (Roadworks, Stationary vehicle, Emergency vehicle approaching, Dangerous Situation (Emergency) electronic brake light)	DENM	10Hz	4	-
39	ClosedLanes	DENM	10Hz	4	-
40	LanePosition	DENM	10Hz	4	-
41	Participants ready	iCLCM	1 Hz	4	-
42	Start scenario	iCLCM	1 Hz	4	-
43	EoS (End of Scenario)	iCLCM	1Hz	4	-
44	Reserve/spare/future use	iCLCM	-	4	-
45	Reserve/spare/future use	iCLCM	-	4	-
46	Reserve/spare/future use	iCLCM	-	4	-
47	Container mask	CAM/DENM/iCLCM	25Hz	1	Indicates presence of container

Table A.2: The local message protocol is shown for packing and unpacking CAM data packets from the Vehicle Adapter which is built on top of GeoNetworking library in Java. The table is based on the Vehicle adapter's documentation [12].

Message part:	Bytes:	Data:	Notes:
Header	1	Message ID	= 2 for CAM
	4	Station ID	Unique station ID
	4	GenerationDeltaTime	
Container Mask	1	ContainerMask	
Basic Container	4	StationType	
	4	Latitude	
	4	Longitude	
	4	SemiMajorConfidence	
	4	SemiMinorConfidence	
	4	SemiMajorOrientation	
	4	Altitude	
High Frequency Container	4	Heading	
	4	HeadingConfidence	
	4	Speed	
	4	SpeedConfidence	
	4	VehicleLength	
	4	VehicleWidth	
	4	LongAcceleration	
	4	LongAccelerationConfidence	
	4	YawRate	
	4	YawRateConfidence	
(opt) Low Frequency Container	4	VehicleRole	

Table A.3: The equivalent table for DENM is shown here for the message fields. The table is based on the Vehicle adapter's documentation [12].

Message part:	Bytes:	Data:	Notes:
Header	1	Message ID	= 1 for DENM
	4	Station ID	Unique station ID
	4	GenerationDeltaTime	
Container Mask	1	ContainerMask	
Management Mask	1	ManagementMask	
	4	DetectionTime	
	4	ReferenceTime	
	4	(opt) Termination	
	4	Latitude	
	4	Longitude	
	4	SemiMajorConfidence	
	4	SemiMinorConfidence	
	4	Altitude	Not in GCDC documents
	4	(opt) RelevanceDistance	
	4	(opt) RelevanceTrafficDirection	
	4	(opt) ValidityDuration	
	4	(opt) TransmissionIntervall	
	4	StationType	
(opt)Situation Container	1	SituationMask	
	4	InformationQuality	
	4	CauseCode	
	4	SubCauseCode	
	4	(opt) LinkedCauseCode	
	4	(opt) LinkedSubCauseCode	
	0	(opt) EventHistory	Not implemented
(opt) Location Container	0	LocationMask	Not implemented
	0	(opt) EventSpeed	Not implemented
	0	(opt) EventPositionheading	Not implemented
	0	Traces	Not implemented
	0	(opt) RoadType	Not implemented
(opt) Alacarte Container	1	AlacarteMask	
	4	(opt) LanePosition	
	0	(opt) ImpactReducationContainer	Not implemented
	4	(opt) ExternalTemperature	
	0	(opt) RoadWorksContainerExtended	Not implemented
	4	(opt) PositioningSolution	
	0	(opt) StationaryVehicleContainer	Not implemented

Table A.4: The equivalent table for iCLCM is shown here for the message fields. The table is based on the Vehicle adapter's documentation [12].

Message part:	Bytes:	Data:	Notes:
Header	1	Message ID	= 10 for iCLCM
	4	Station ID	Unique station ID
Container Mask	1	Container Mask	
High frequency container	4	Rear axle location	
	4	Controller type	
	4	Response time constant	
	4	Response time delay	
	4	Target longitudinal acceleration	
	4	Time headway	
	4	Cruise speed	
(opt) Low frequency container	1	Low frequency mask	
	4	(opt) Participants ready	
	4	(opt) Start platoon	
	4	(opt) End-of-scenario	
MIO	4	Mio ID	
	4	Mio Range	
	4	Mio Bearing	
	4	Mio Range rate	
Lane	4	Lane	
Pair ID	4	Forward ID	
	4	Backward ID	
	4	Acknowledgement flag	
Merge	4	Merge request	
	4	Safe-to-merge	
	4	Flag	
	4	Flag tail	
	4	Flag head	
Intersection	4	Platoon ID	
	4	Distance travelled in CZ	
	4	Intention	
	4	Counter	