CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF TRANSPORTATION SCIENCES

Jiří Brož

USAGE OF TECHNOLOGY LTE-V IN V2X APPLICATIONS

MASTER'S THESIS

Prague 2019

LINKOPING UNIVERSITY

DEPARTMENT OF SCIENCE AND TECHNOLOGY

Jiri Broz

USAGE OF TECHNOLOGY LTE-V IN V2X APPLICATIONS

MASTER’S THESIS

CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Transportation Sciences
Dean's office
Konviktská 20, 110 00 Prague 1, Czech Republic

K620..Department of Transport Telematics

MASTER'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Bc. Jiří Brož

Code of study programme code and study field of the student:

N 3710 – IS – Intelligent Transport Systems

Theme title (in Czech): **Využití technologie LTE-V v aplikacích V2X**

Theme title (in English): Usage of Technology LTE-V in V2X Applications

Guides for elaboration

During the elaboration of the master's thesis follow the outline below:

- Analysis of cooperative systems implemented in CR and Europe.
- Analysis of telecommunication technologies suitable for usage in cooperative systems (ITS-G5, LTE-A, LTE-V).
- Evaluation of the use cases defined for ITS-G5 also in LTE-V technologies (incl. transmitted message and safety mechanism).
- Proposal of testing methodology and scenarios for verifying LTE-V technology.
- Lab verification of technology LTE-V and evaluation of the results.

Graphical work range: 10 pictures at least.

Accompanying report length: At least 55 pages of text (incl. figures and tables as parts of the report).

Bibliography:

Zelinka,T., Svítek, M.: Telekomunikační řešení pro informační systémy síťových odvětví, Grada 2009

ETSI, CEN a ISO standards

Expert articles

Master's thesis supervisor:

doc. Ing. Zdeněk Lokaj, Ph.D.

Ing. Martin Langr, Ph.D.

Vangelis Angelakis, Dr.

Date of master's thesis assignment: **July 27, 2018**

(date of the first assignment of this work, that has be minimum of 10 months before the deadline of the theses submission based on the standard duration of the study)

Date of master's thesis submission: **May 28, 2019**

a) date of first anticipated submission of the thesis based on the standard study duration and the recommended study time schedule
b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

L. S.

Ing. Zuzana Bělinová, Ph.D.
head of the Department
of Transport Telematics

doc. Ing. Pavel Hrubeš, Ph.D.
dean of the faculty

I confirm assumption of master's thesis assignment.

Bc. Jiří Brož
Student's name and signature

Prague .... July 27, 2018

Declaration

I hereby submit for the evaluation and defense the master's thesis elaborated at the CTU in Prague, Faculty of Transportation Sciences.

I have no relevant reason against using this schoolwork in the sense of § 60 of Act No. 121/2000 CoIl, on Copyright and Rights Related to Copyright and on Amendment to Certain Acts (the Copyright Act)

I declare, I have accomplished my final thesis by myself and I have named all the sources used in accordance with the Guideline on ethical preparation of university final theses.

Prague 24th of May Jiří Brož

Acknowledgements

Firstly, I would like to express my gratitude to all of my supervisors, to Vangelis Angelakis, for willingness and help, to Martin Langr, who I participate in several projects with. We have cooperated from the early years of my studies at CTU and it is really appreciated that our cooperation is still working. And especially to Zdeněk Lokaj, who helped me to find a topic of the thesis, involved me in the project C-Roads and provided me important contacts related to the project. He supported me from the beginning of my work on this final thesis till the end.

Next thank is devoted to Martin Šrotýř and Tomáš Zelinka. They have been always available for discussion and gave me practical hints and several recommendations, helped me with visualization of the results and provided me expert articles related to the topic.

The cooperation with company T-Mobile Czech Republic is also highly appreciated, especially with Petr Horák, who helped me with testing of the units and evaluation. Without this cooperation could not be possible to have any relevant output of this thesis.

Finally, I would like to thank all of my family members for support during the studies and help over the last years.

Abstract

The subject of the master thesis „Usage of technology LTE-V in V2X applications" is analysis of cooperative intelligent transport systems with mainly focus on the technology LTE-V. Within the work is also analyzed current state of C-ITS deployment, their use cases, other technologies as an alternative of LTE-V, measuring of specific parameters and evaluation of LTE-V.

Number of pages: 66

Keywords: C-ITS, LTE-V, V2V communication, cellular network, LTE-V testing.

List of abbreviations

3GPP – The Third Generation Partnership Project

CAM – Cooperative Awareness Message

C-ITS – Cooperative ITS

DENM –Decentralized Environmental Notification Message

eNB – eNodeB (base station in E-UTRA network)

E-UTRAN – Evolved Universal Terrestrial Access Network

ITS – Intelligent Transport Systems

ITS-G5 – Intelligent Transport Systems operating in 5GHz band

I2I – Infrastructure to infrastructure communication

I2V – Infrastructure to vehicle communication

LTE – Long Term Evolution

LTE-A – LTE Advanced

LTE-V – LTE for vehicles

OBU – On-board unit

PC5 – interface of direct communication in LTE-V

PLMN – Public Land Mobile Networks

RSU – Road-side unit

UE – User Equipment

Uu – interface for indirect (cellular based) communication in LTE-V.

V2I – vehicle to infrastructure communication

V2N – vehicle to network communication

V2P – vehicle to pedestrian communication

V2V – vehicle to vehicle communication

V2X – vehicle to “something” communication

Table of contents

Introduction 8

1.1 Motivation 8

1.2 Aim of study 8

1.3 Limitations 9

1.4 Outline 10

2 C-ITS Background 12

2.1 Communication approaches 12

2.1.1 V2V *12*

2.1.2 V2I *13*

2.1.3 V2P *14*

2.1.4 V2N *14*

2.1.5 I2I *15*

2.2 C-ITS deployments, pilots and trials 15

2.2.1 United States *16*

2.2.2 Australia *16*

2.2.3 Asia *17*

2.2.4 Europe *17*

2.3 Used telecommunication technologies in C-ITS 22

2.3.1 ITS-G5 .... *22*

2.3.2 LTE technologies *23*

3 LTE–V technology 25

3.1 LTE Sidelink transmission modes 27

3.1.1 Centralized scheduling (Mode 3) *28*

3.1.2 Distributed scheduling (Mode 4) *30*

4 Methodology 32

4.1 Testing methodology 32

4.1.1 Used equipment *32*

4.1.2 Testing procedure *34*

4.1.3 Output from the measuring *37*

4.2 Evaluation methodology 37

4.2.1 Structured data acquisition *38*

4.2.2 Evaluation of the data ... 40

4.3 Verification ... 43

5 Results ... 46

Conclusions ... 53

5.1 Discussion ... 53

5.2 Recapitulation ... 54

5.3 Future outlook ... 55

References ... 57

List of figures ... 65

Introduction

This master thesis is focused on the intelligent transport systems (ITS) specifically on cooperative systems in transportation, also named as cooperative intelligent transport systems (C-ITS). The main consideration should be given in technology LTE-V, its usage and advantages for C-ITS applications.

1.1 Motivation

As an author of the thesis, I would like to mention this topic has been chosen because of my interest in these smart technologies, which could improve traffic conditions on the highways, but also in the city centers. It seems that cooperative systems are an essential part in the process of becoming automated vehicles or at least an important part with futuristic vision, but still without strictly predefined approach, how these systems should be working. The important point of my motivation is also that the field of C-ITS can provide solution helpful for traffic accidents avoiding and which makes mobility safer.

The LTE-V technology was stated as aim of the thesis after the discussion with one of my supervisors, because this technology is relatively new and can be implemented across the Europe as complementary solution to currently deployed ITS-G5. In overall, the coexistence of these technologies can improve C-ITS.

1.2 Aim of study

Within the work be supposed to analyze the current state of C-ITS deployment within the Czech Republic and also European-widely, prepare the specific scenarios for testing of LTE-V technology and make an evaluation. The main objective is to come up with conclusions, why LTE-V is suitable for its usage in C-ITS and compare it with other technologies, if possible.

1.3 Limitations

The scope of the thesis is specified to achieve a testing of relatively new technology LTE-V. For the testing itself and evaluation is required to have an equipment such as antennas, vehicles, vehicle units etc. In general, it is necessary to own or at least to have access during the time of measuring or evaluation to the specific hardware as well as software.

In terms of mentioned requirements and very high costs, the cooperation with other participants on the same project is at least recommended, but also highly appreciated. The participation on the project brings some benefits and enhancements, but sometimes it has also some unsuspected pitfalls. The final outcome of the thesis can be affected by several issues such as delays or fulfilling of the project subtasks.

The testing of LTE-V depends on the related project cooperation, especially on the development and installation of the units, this may affect the testing itself. The number of tested scenarios can be also influenced by unexpected circumstances. In the case of delayed measuring and testing, the evaluation of LTE-V technology should be made based on the theoretical models or public tests worldwide. In the case that number of possible tested scenarios will be affected by mentioned circumstances, the evaluation of predefined usecases for ITS-G5 technology would not be possible to provide.

The availability of other technologies depends on the related project cooperation, so the comparison of LTE-V with other technologies can be impossible, due to the lack of necessary equipment for measuring. In the case that only LTE-V technology will be tested without other technologies, the results should not be assumed as a complementary solution in C-ITS, due to the possible and especially unverified radio interference.

1.4 Outline

For better understanding, this chapter introduces the thesis structure in step-by-step description model on the Figure 1: Thesis outline. This visualized proposal is contained from the basic steps, that makes together a procedure of frameworks to reach the results and conclusions.

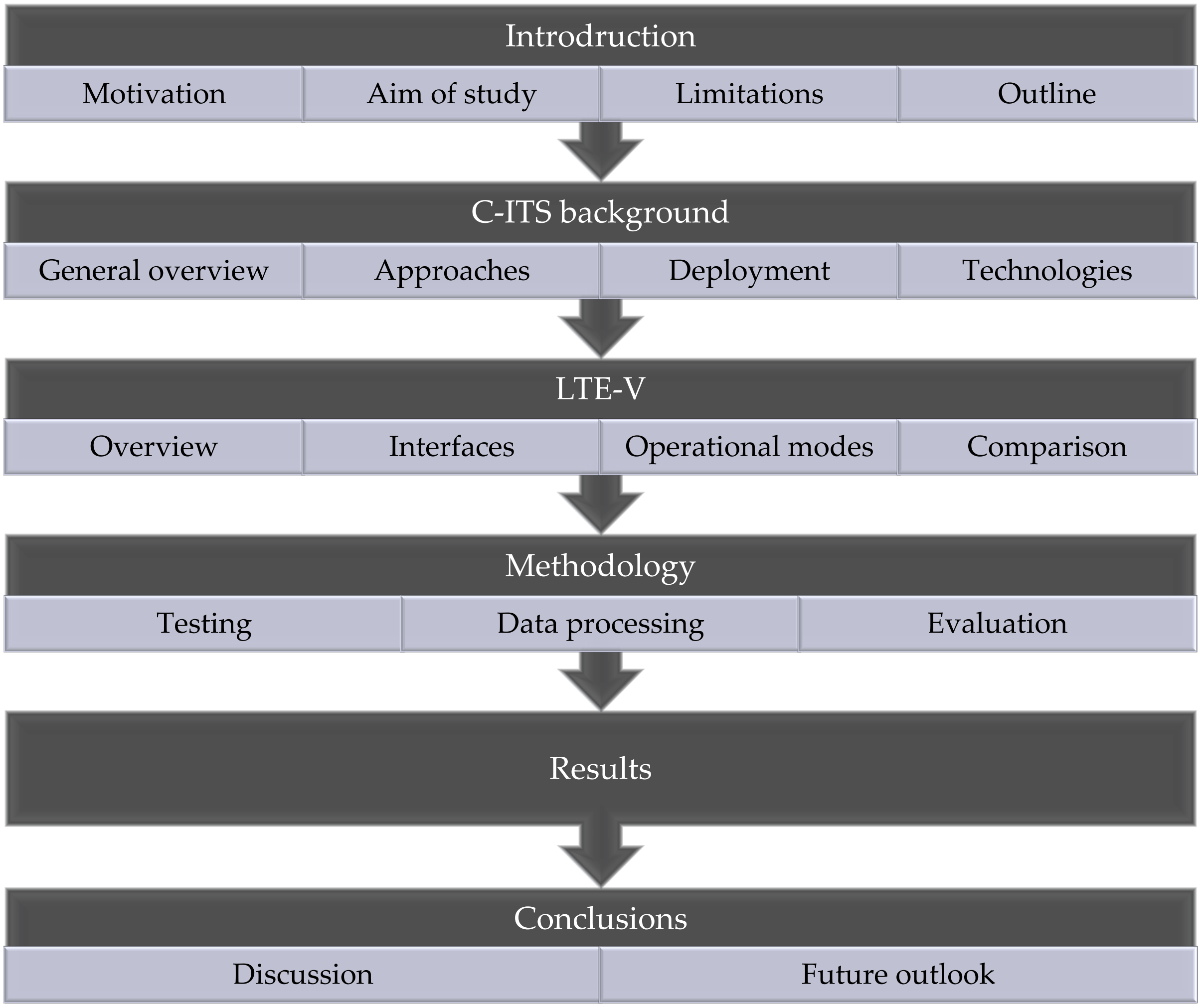


Figure 1: Thesis outline.

According to these mentioned particular objectives, the work progress of the thesis has been made as well as the structure of the text part.

The second chapter is mainly focused on the already implemented solutions within the cooperative intelligent transport systems. The first part provides a general overview, to all of the readers, who are not involved in that highly changing and evolving field of transportation. Within this part, benefits are described as well as the communication approaches. Then the topic is slightly changed to deployments of cooperative systems and to the description of technologies, which are used especially in the Europe.

The third chapter is assigned to the technology LTE-V as a main research part of the thesis. The general information is written as well as a description of the interfaces used for communication, improvements and enhancements of technology LTE as basis of the LTE-V technology and modes of operation using sidelink communication, that can be used for the vehicular communication as an alternative to the current deployed technology ITS-G5.

Within the next chapter the methodology is defined. The methodology is contained of several parts such as testing of LTE-V, Data Processing and Evaluation.

As an outcome of the thesis, in the pre-last chapter, the results from the measuring and evaluation are mentioned. The last chapter is devoted to the conclusions, improvements and recommendations, what to do within the analyzed field in the future.

2 C-ITS Background

The cooperative systems are an essential part of ITS. Based on that fact, cooperative systems are usually marked as C-ITS. This field is known as a combination of telecommunications and informatics within the transportation systems to ensure less traffic congestions, reduction of air pollution, better estimation of travel time, traffic efficiency and safety. [1]

2.1 Communication approaches

The core principle of C-ITS is a sharing of valuable information among the cars and infrastructure in the specific area. This distribution of the messages is provided in several different approaches. All of these approaches are named as V2X communication, which represents "vehicle – to – something". All of the messages have to follow the specified standards of operation, which is described in the next chapters. In summary, the V2X communication is the wireless data exchange between actors on the road and ITS stations or vulnerable users around. This exchange provides vehicles with knowledge of theirs surrounding environment and ability to virtually see around the corner. [2]

2.1.1 V2V

As possible to observe from the name V2V ("vehicle–to–vehicle"), the first case of communication is exactly between two vehicles. The main principle is that each car should send information about itself to each other on the road. This type of communication provides the ability of the vehicle to share information for example about emergency braking to the following vehicle.

Figure 2: V2V communication.

2.1.2 V2I

The second approach is named as "vehicle–to–infrastructure" communication. This communication can be used for example to optimize intersection control. The arriving vehicle would send information about its position (presence in specific area before the intersection) to the controller in advance, where this information should be processed and based on the priority or demand of vehicles, green light would be switched on for specific direction. There are several different use cases of V2I communication, and surely, it works the other way around, the roadside unit (infrastructure) can send a message to the vehicle for example about an obstacle on the road or expected delay. In some sources this opposite communication is specifically named as I2V ("infrastructure–to–vehicle"). [3]

a) V2I communication

b) I2V communication

Figure 3: V2I and I2V communication.

2.1.3 V2P

V2P communication is the next approach, which represents data exchange between vehicle and pedestrian or any other vulnerable road user. This communication requires pedestrians, who are also equipped with units as well as vehicles. As you can imagine, this user equipment is not accepted by all of the people along the road. Some of the people don’t want to be somehow monitored and that is the main challenge of V2P communication – to involve most of the people. Several studies point out to the fact, that almost everyone uses own mobile phone, which can be utilized for this type of application. [4]

Figure 4: V2P communication.

Due to the fact, that traffic accidents occurring pedestrians and other vulnerable road users belong to the group with the highest impact on the health - especially serious injuries and deaths, is necessary to keep this approach within the vehicular communication in minds. [5]

2.1.4 V2N

The communication V2N is used especially in the cellular network communication, where the vehicles communicate with base stations around. This communication requires coverage of the signal. The V2N communication can be used not only for the data transmission, but also for the network assistance or management of direct communication among the vehicles. In LTE-V technology, this communication is named as LTE-Uu - based on the interface. The communication from the vehicle to network is almost every time as unicast transmission, while communication from the network can be unicasted and also broadcasted to all of the vehicles around. [6]

Figure 5: V2N communication.

2.1.5 I2I

The additional specific approach is named as I2I ("infrastructure–to–infrastructure") communication, which guarantees the distribution of the information through the infrastructure network. From the name, it is obvious, that communication is not among the vehicles, but among the nodes on the infrastructure side. This communication provides information such as the weather condition from the meteostation to variable message signs situated along the road. [3]

2.2 C-ITS deployments, pilots and trials

The implementation process and testing of C-ITS is worldwidly spread. These systems are supported by several technologies, different methods of using radio spectrum are defined based on the applications and also the control over the systems is different for specific approaches.

In this chapter is mentioned current status of C-ITS deployments. The structure of this chapter is a list of the projects, which have been implemented worldwide with main focus on the Europe. Each of the project contains small description, what has been already done, implemented or at least tested.

2.2.1 United States

THEA Connected Vehicle Pilot

This pilot program is deployed in US in Tampa. Within the project more than 1000 vehicles (privately owned) and 18 public transportation vehicles are equipped with On-Board-Units (OBU). 46 Road-Side-Units (RSU) are installed in the area. The applications are forward collision warning, pedestrian collision warning, intelligent control system on the intersections, wrong way entry…etc. [7]

NYC Connected Vehicle Project

Up to 8000 OBU and 353 RSU (approximately 310 controlled intersections). In the NYC these types of application are used – blind spot warning, lane change warning, red light violation warning, oversize vehicle warning, pedestrian in signalized crosswalk warning and others. The project is right now in the final phase of operation and maintenance. [8] [9]

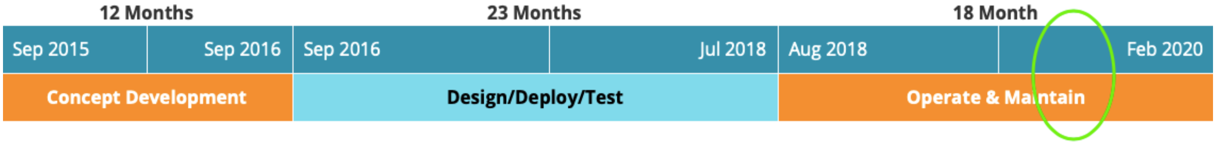


Figure 6: Current status of the project. [10]

2.2.2 Australia

Cooperative Intelligent Transport Initiative (CITI)

The CITI is a first testing facility of C-ITS in Australia. Based on the number of installed units seems that focus is mainly on the trucks – up to 60 trucks, 11 public buses, 7 RSU. The system provides information such as intersection collision warning, red light alert and speed limit information. [11] [12]

Telstra and its trial

The company Telstra is the mobile network provider, in 2016 they started the first trial in participation with Cohda Wireless. They tried to find an independent solution from government funded initiatives (ITS-G5, DSRC). The first trial validated the C-ITS possibility using 4G technology in V2I communication. This participation successfully continued, and the testing took place over LTE Uu interface (part of LTE-V technology). Next trial is commencing in the last months of 2019, the connectivity of 500 vehicles and RSU is expected. [13] [14] [15]

These trials confirmed that 4G technology (in future 5G networks) can support several applications such as alert to the driver about roadworks ahead, giving green light to preferred vehicles, optimal green light timing and optimal speed information to pass the intersection fluently. [16]

2.2.3 Asia

C-ITS Pilot program in Korea

By 2016 was provided the first distribution of OBU in the pilot area and till 2020 is expected OBU penetration rate around 10%, the planned expectation is 50% OBU penetration rate till 2025 and rate for 2030 is estimated as 70%. The application includes 15 core functions such as WAVE communication-based toll collection system, road work zone warning, emergency vehicle approaching alert...etc. [17] [18] [13]

2.2.4 Europe

SCOOP

The SCOOP project is a pilot for deploying C-ITS across the France, the main target is to install OBU in 3000 vehicles and cover more than 2000 km of highways. The data exchange is provided as a short-range communication – named as ITS-G5, which is designed purposely for C-ITS usage. [19]

Since 2016 mobile provider joined the project and also participation with Spain, Portugal and Austria with objective of cross-testing has begun. The project is co-financed by European Union (EU) and estimation for the next phases is to be focused for developing new technology such as hybrid ITS-G5 or cellular usage and also new services should be specified. [19]

NordicWay

The NordicWay is a real-life deployment pilot. This project provides the network in four nordic countries – Finland, Sweden, Norway, Denmark. The first phase of the project was ended in 2017 and the second phase has started – this phase is named as NordicWay2. [20]

The project is based on the cellular communication, which provides the sharing of information from end devices, through the specific cloud to the interchange node, which is the key node of the system. All of the information is broadcasted from this central point to end-devices as well as to the traffic management centre of each participating country. The short-range communication such as V2V or V2I is ITS-G5 based. [21]

During the first phase, only the specific corridors were tested. These corridors are in a high-quality coverage area. That is the reason, why other parts of countries should be tested in the second phase. It is necessary to explore a blind spot and identify the state of coverage. The interoperability in cross-bordering scenario should be also solved. [22]

Talking Traffic

Talking traffic is a Dutch partnership, which provides collaboration between ministry, local and regional authorities and public companies as well as international ones. This cooperation is relatively new, and it has started in the last year. The first live service was launched in the last year and offers the ability to receive warnings about traffic jams ahead, local weather condition changing...etc. [23] [24]

The aim of the partnership is to share the knowledges from different fields and provide the solution, which makes the road users informed. Expected applications are for example warnings about emergency vehicles, speed limit as well as recommendation about efficient speed according to the traffic stream, intersection control and other traffic conditions to ensure smoothly driving...etc. [25] [26]

Cooperative ITS Corridor

The Cooperative ITS Corridor is a project based on the contribution of Netherlands, Germany and Austria. The project has started in 2013 with research and development phase, followed by phase of testing, but nowadays the C-ITS corridor rolled-out. [27]

In 2017 was the phase of trials and around 100 tests for 53 different scenarios was evaluated. These tests were carried out around the city Frankfurt under the real road conditions. During the tests, the technology ITS-G5 for short-range communication was used. The results fulfilled the expectations, that ITS-G5 can be used in deployment of C-ITS in regular operation. [28]

InterCor

InterCor also named as interoperable corridors is European project with the main objective to connect all of the C-ITS projects around. Within InterCor the SCOOP project from France, C-ITS corridor (Netherland, Germany, Austria), UK and Belgian initiatives are involved. The plan of the project is to provide the C-ITS network to achieve cross-border interoperability and continuity of the systems via ITS-G5 and cellular communication or combination of both approaches. [29] [30]

C-ROADS

The C-Roads project is co-financed by Connecting Europe Facility, it covers all of the European deployments with main goal to work together on interoperable C-ITS services across the Europe. It is an initiative among the European member states and operators of the roads to cooperate on the testing and deploying of C-ITS to reach the solution, where interoperability and cross-border harmonization is guaranteed. [31] [32]

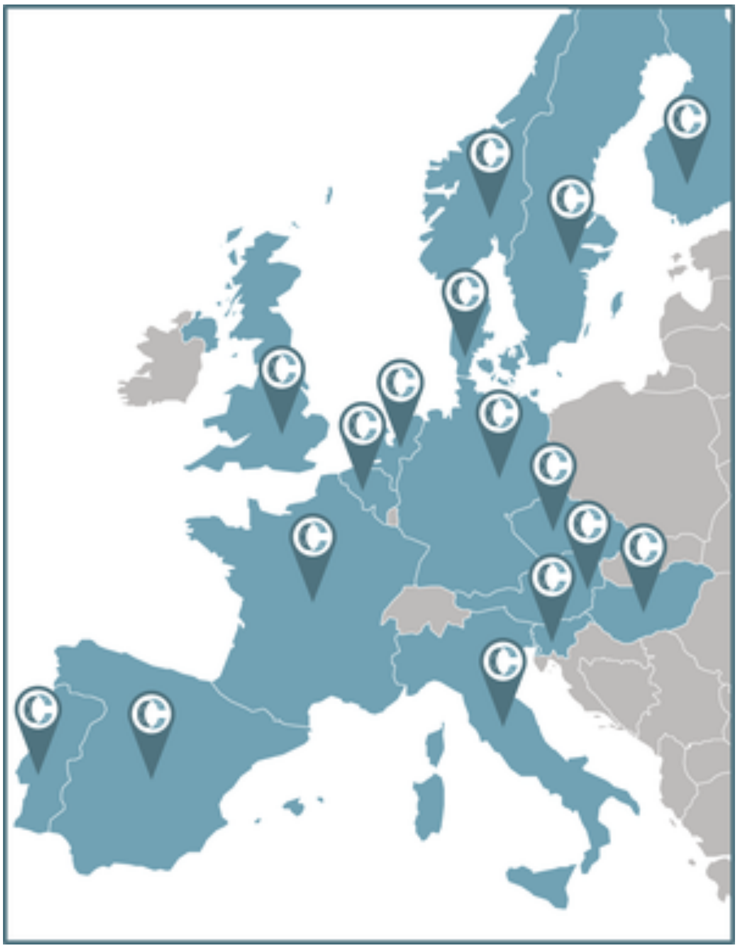


Figure 7: Core members of project C-Roads. [33]

C-ROADS Czech Republic

The Czech Republic is also participating on the C-Roads platform. The Czech Republic is one of the core members and the role is stated as for anyone other in the project. The general aim is to work on C-ITS deployment according to the other states in order to achieve interoperable solution for all the European users. One interesting point is that C-Roads platform was initiated in 2015 by Germany, Austria and also Czech Republic. The significant objective is to verify coexistence, reliability and mainly security of hybrid communication as a complementary solution using LTE-V and ITS-G5. One of the goals is to verify C-ITS deployment for the railway crossing scenarios with effort to recognize possibilities, how to avoid a collision by using C-ITS. [34] [35]

Figure 8: C-Roads deployment in Czech Republic. [36]

The C-ITS are deployed on several highways in Czech Republic – highway D0 (Prague ring road), highway D1 (connecting two biggest cities in Czech Republic – Prague, Brno), highway D5 connecting Prague with Pilsen and D11 from Prague to Hradec Kralove. C-ITS systems are also installed in Pilsen and Ostrava, where are used as a support of public transportation. One pilot site will be close to Pardubice, where information about railway crossing will be tested. And finally, the cross-border testing to ensure the interoperability with other European states. [37]

BaSIC

The BaSIC was the first project in Czech Republic related to the testing of C-ITS. This project took a place in 2013 and test area was on the Prague ring road. The testing was made with main objective to provide information to the vehicle going on the road (in real conditions). Two types of information were transmitted. The first case was to provide a data exchange from variable message signs on the road directly to the vehicle going around. The second case was focused on the data exchange between two vehicles. This scenario simulated communication between "normal" vehicle and emergency vehicle, with goal to receive information about emergency in advance. [38]

2.3 Used telecommunication technologies in C-ITS

In this subchapter is an overview about the telecommunication technologies that can be used for the C-ITS purpose to ensure interoperability and compatibility of the system. These technologies can be used in two different ways:

- Short-range communication,
- Longer-range communication.

In Europe for short-range communication is used the standardized ITS-G5 technology, which operates in a dedicated frequency 5,9 GHz. For communication on longer distance the cellular technologies can be used, because of the coverage of already implanted stations and existing network. These cellular technologies such as 3G or 4G already provide a good solution and coverage area in large part of European Union. [39]

The special case is a "hybrid communication", based on a key principle to combine both types of communication and thus creates the complex system. The purpose of the hybrid communication is to maximize benefits via combination of different and complementary solutions. The second key principle is an independence of the system on the specific telecommunication technology, that allows effortless integration for new technologies in the future. [39] [40]

2.3.1 ITS-G5

ITS-G5 is the type of communication developed specifically to the vehicular data exchange purposes. ITS-G5 is based on IEEE 802.11p protocol. This technology has been tested and already deployed across the European states. As is written in the general description on the previous page, ITS-G5 is the standard used for short range communication and it is operated in 5,9 GHz frequency bandwidth. [39] [40]

The similar technology as ITS-G5 is also provided outside from the Europe and it is named as WAVE (Wireless Access in Vehicular Environments) or DSRC (Dedicated

Short Range Communication). ITS-G5 does not require a network coverage or RSU along the road for data exchange purposes. [41]

The technology is being accepted by car manufactures and that makes the technology even more important. The company Cadillac already implemented mentioned technology in their cars – specifically to the model CTS Sedan, with promise to handle up to 1000 messages per one second. Other branded vehicle factories also announced that technology DSRC is the way of their strategy. Toyota and Lexus promised implementation of DSRC in 2021 and the same initiative is promised by Volkswagen on the European market with technology ITS-G5. [42] [43]

2.3.2 LTE technologies

The LTE (Long Term Evolution) was firstly specified in 3GPP Release 8. The motivation for this at the time new technology was a user demand for higher data rates and quality of services, continued demand for cost reduction, need to ensure the system, that can fulfill the future challenges and other technical aspects. An access network of LTE technology, in some sources named also as E-UTRAN (Evolved Universal Terrestrial Access Network), is the access network connecting eNB (eNodeB) stations without any centralized intelligent controller to core network. [44]

The main requirements for developing and deploying new technology were high spectral efficiency, high peak data rates, short round trip time together with flexibility in frequency and bandwidth. [44]

The solution of this access network is based on Orthogonal Frequency Division Multiple Access, high order modulation (64QAM), large bandwidths (up to 20MHz) and Multiple Input Multiple Output technology. [44]

LTE-A

LTE-A also named as LTE Advanced is an extension of "classic" LTE technology. This update was highlighted as a transition from the 3rd generation of mobile technology to the 4th generation. This evolution of LTE was made for the purpose of data rates increasing in a cost-efficient way and to strictly follow the ITU (International Telecommunication Union) requirements for the next generation services, such as: increased peak data rate for uplink (1,5Gps) as well as downlink (3Gps), higher spectral efficiency to 30bps/Hz, increased number of simultaneously active users and improved performance at the edge of cells. [45]

During the implementation of LTE-A, new functionalities as carrier aggregation, multiple antenna usage and support for relay nodes were introduced.

LTE-V

LTE-V is an extension of LTE technology, specifically for vehicular communication. Due to the scope of the thesis, the description of LTE-V technology requires more space to explain it well. For the whole expression, how the technology works, is used following chapter 3 – LTE–V technology.

3 LTE–V technology

The LTE-V technology is named in several sources as LTE-V2X, or generally for all of the cellular systems as Cellular-V2X or C-V2X, where C refers to 4G – LTE but also including 5G new radio releases. These cellular technologies optimazed for vehicular data exchange provide network based communication (V2N) that has been used as well as a new mode of operation defined in 3GPP (3rd Generation Partnership Project) release 14, that allowed direct V2V and V2I communications without cellular network coverage requirement. In the technical terminology these communications are marked based on the interface. The V2N communication is also known as Uu, whereas direct communication V2V and V2I is known as PC5, based on the interface. [46]

Within LTE-V technology is also neccesary to mention the V3 interface, that allows communication between an UE (User Equipment) and V2X Control function. This function provides authorization and provisioning of specific parameters for V2X communication to UE. [47]

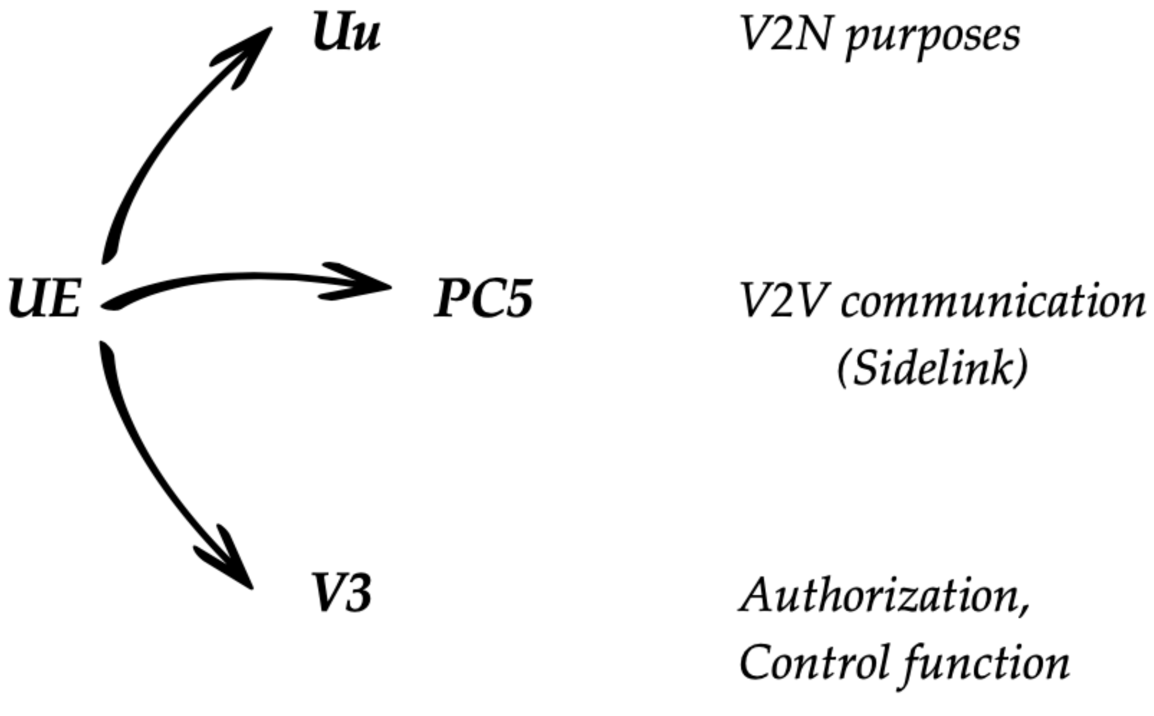


Figure 9: LTE-V communication interfaces. [47]

To achieve LTE-V support for V2X communication, these requirements should be followed:

- Maximum message transfer latency to 100ms (in specific scenarios maximum allowed latency is only 20ms),
- Message size up to 1200 bytes,
- Support of up to 10 message transfer per second (with maximal message transfer frequency 50Hz),
- Communication range should provide sufficient response time for a driver (around 4 seconds),
- Support of relative vehicle speed up to 500 kmph,
- Support communication in and out of network coverage. [47]

On the previous page mentioned interfaces can be used by UEs independently for transmitting of the data and for the reception, so that is possible to send the data over the PC5 to another vehicle and receive data via LTE-Uu at one moment [47]

The LTE-Uu interface is used for communication between UEs and the eNBs around. This provides network communication dependent on the cellular coverage. UE can send the data via uplink through the eNBs to the locally relevant V2X application server and receive data via unicast or broadcast downlink communication. Broadcast (Multicast) delivery to UEs is locally routed in terms to ensure latency improvents. [47]

For the purpose to share the information from vehicle to vehicle is necessary to use indirect communication via uplink to the network and then the information can be broadcasted via downlink to all of the vehicles around the eNB stations as well as unicasted to the specific vehicle. [48] [47]

The possible indirect communication over Uu interface is illustrated on following picture.

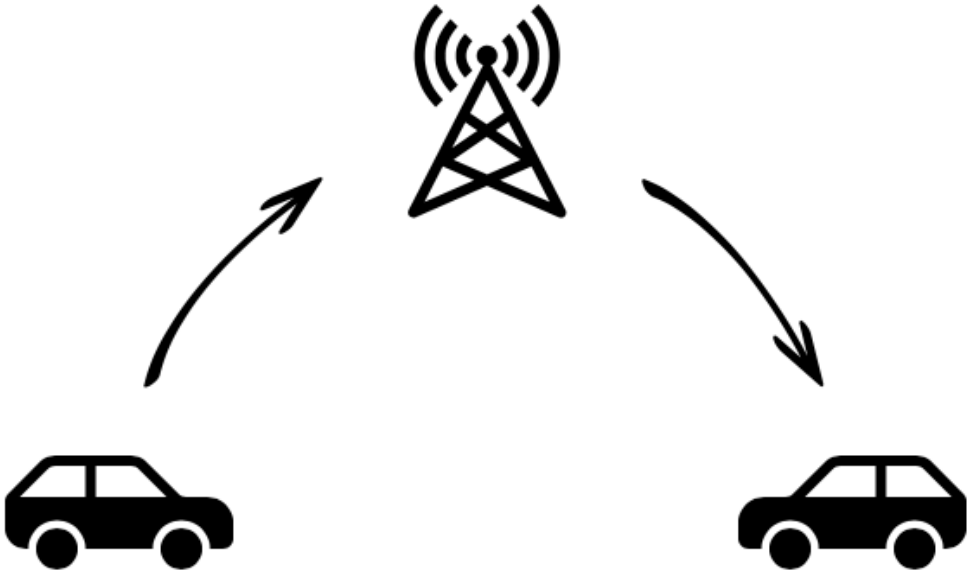


Figure 10: V2V indirect communication over LTE-Uu interface.[1]

For the V2V purposes is more suitable direct communication also reffered as a Sidelink communication over the PC5 interface, that can be operated by vehicles independetly on the cellular coverage. This fact makes LTE-V technology as an alternative to ITS-G5 communication among the vehicles. In the release 14 allocated frequency spectrum 5.9 GHz for ITS purposes is taken into the consideration. [47] [48]

3.1 LTE Sidelink transmission modes

The communication modes are specified by 3GPP. First two modes of operation were designed in terms of battery lifetime (mobile devices) extension. This objective was reached by increasing of latency, which is not suitable for vehicular data exchange. In purpose of communication among the vehicles, the low latency and high reliability are required, therefore the next two modes were introduced in the release 14. The main difference is based on the network assistance. [48]

---

[1] The mentioned figure is a creation of the thesis author. The depicted idea is based on the 3GPP Release 14 - mentioned as a source [47]

PC5 communication works in the same way as device-to-device comunication, also named as sidelink at the physical layer, but for the V2V cases, where the high speed and density is required. In that case some of the fundamental improvements were introduced:

- Additional symbols dedicated to the transmission of demodulation reference signals to ensure uneffected communication at high speeds by Dopler effect,
- New scheduling assignment to improve system performance under the high density of the UEs together according to the latency requirements,
- Sensing with semi-persistant mechanism for distributed scheduling. [47]

Based on it two deployment configuration are defined. The first one is a Centralized eNB scheduling (reffered as a Mode 3) and Distributed scheduling (as a mode 4). Both of them support direct V2V communications but differ on how they allocate the radio resources. [47] [48]

3.1.1 Centralized scheduling (Mode 3)

The mode 3 is used when UE is served by E-UTRAN. It requires attandance of the units inside the celullar network coverage area and that is the reason, why is it also named as eNB scheduling. The V2V traffic management is controlled by eNBs around via control signaling. [48]

Althought the communication is managed by cellular network, the standard does not implicitly specify the resource management algorithm. It gives the possibility to mobile operators to implement their own solution, but still it is necessary to follow one of these scheduling methods:

- Dynamic scheduling,
- Semipersistant scheduling. [48]

Dynamic scheduling

During each packet transmission, the specific subchannel from the vehicle to the eNB has to be requested. There is no reservation system for subchannel allocation. Due to this, packet delays and cellular signaling overhead are increasing until the notification (about subchannel assigning) is received in the vehicle. [48]

Semipersistant scheduling

The subchannel for the periodic transmissions between the vehicle and eNB has to be reserved before. The eNB manages the reservation and should define the time dedicated for the transmission. This eNB reservation management includes activation, deactivation and modification of subchannels. At the start of the transmission vehicle has to provide an information about the size, priority and frequency of transmission. Based on this information, eNB reserves (various length of reservation) subchannel - assigned for the communication. When the subchannel is assigned, the transmission is in progress. If any change of the mentioned parameters happened during the transmission, then the vehicle has to inform the eNB. [48]

In a case that vehicular communication operated under the mode 3 can be provided by several mobile operators and the assigning of the subchannels for communication is not strictly predefined, the Inter-mobile network architecture has to be devolep to ensure the interoperability between these networks. The 3GPP has defined an inter-PLMN (Public Land Mobile Network) architecture to avoid packet collisions. [48]

On the following picture is shown schema of the communication over the PC5 interface with network management (stricle required for mode 3).

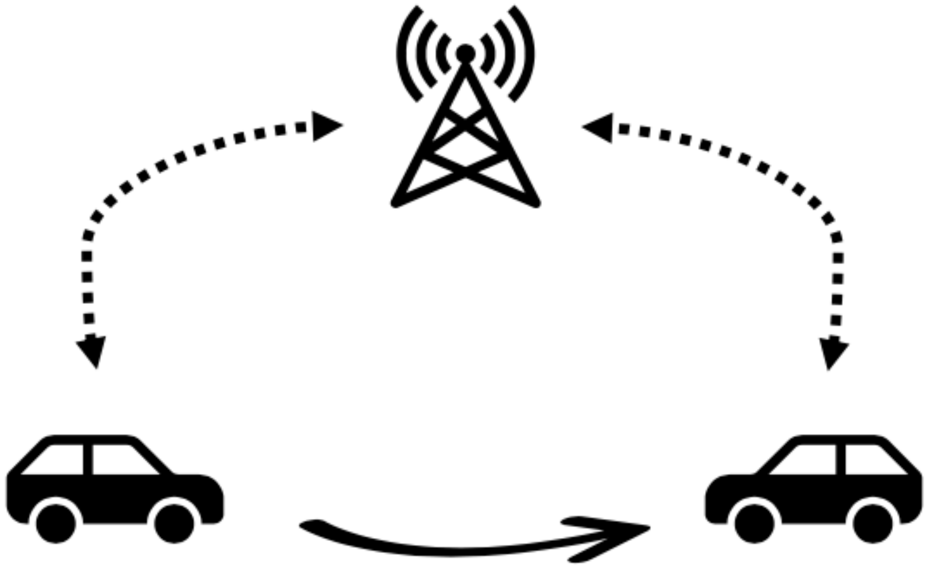


Figure 11: Network managed communication over PC5 in cell. coverage.[2]

3.1.2 Distributed scheduling (Mode 4)

Mode 4 does not require cellular coverage, that is why it is considerad as a baseline mode for direct communication among the vehicles. The mode 4 represents an alternative to 802.11p or dedicated short range communications (DSRC). Although the mode can work autonomously without cellular coverage, it is not exactly independent on the network. The mode 4 provides the ability of the vehicles to work autnomously but when the vehicles are under the coverage of signal, the decision of V2X configuration is on the network side. That is the reason, why mentioned schema (Figure 11: Network managed communication over PC5 in cell. coverage. above works well also in the mode 4, and also why this commucation in mode 4 is named as network assisted communication. [48]

---

[2] The mentioned figure is a creation of the thesis author. The depicted idea is based on the 3GPP Release 14 - mentioned as a source [47]

The network provides the radio resource management and configures the V2X channel. The information about the configuration is sent to the vehicles via sidelink V2X configurable parameters. This message includes information about the carrier frequency of V2X channel, V2X resource pool, synchronization references, subchannelization scheme, number of subchannels and number of resource blocks. Resource management algorithm is stricly defined as opposed to mode 3, so there is no ability of mobile providers to assign subchannels via specific algorithm so that the inter - PLMN architecture is not required. [48]

Out of the cellular coverage vehicles autonomously select their radio resources. When the vehicle goes out of the coverage, it replaces sidelink V2X configurable set of parameters with preconfigured set of parameters. [48]

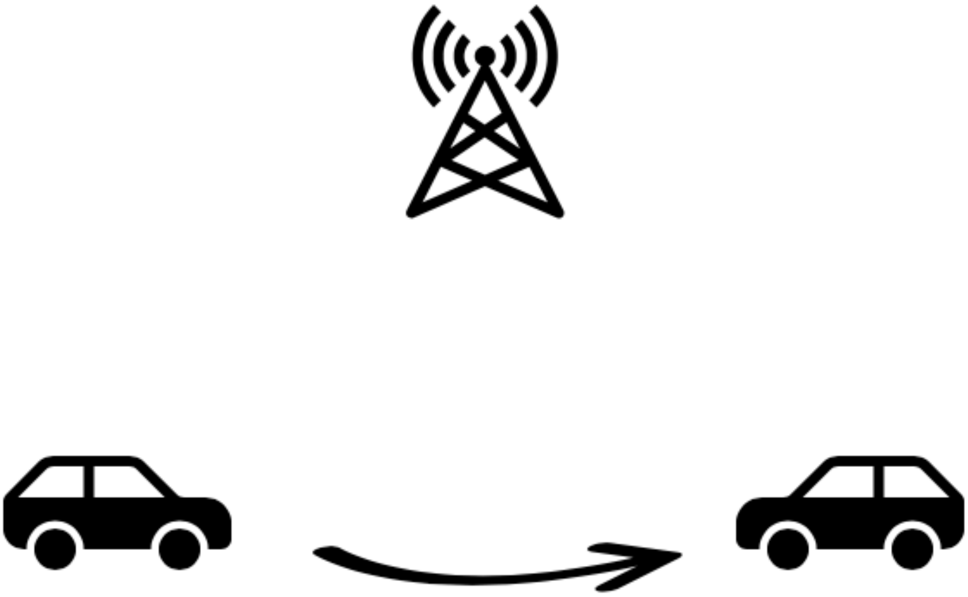


Figure 12: Self-managed communication over PC5 out of cell. coverage.[3]

---

[3] The mentioned figure is a creation of the thesis author. The depicted idea is based on the 3GPP Release 14 - mentioned as a source [47]

4 Methodology

The methodology is structured as follows, the first part of the methodology is intended to describe the testing and the second one contains the procedure of evaluation and data processing.

4.1 Testing methodology

In this chapter is well described process of LTE-V testing – What was tested? Where was it tested? Which devices were used? Which approach (use case) was used and why?

It is necessary to mention, that testing of the technology LTE-V was limited by the delay of the related project. Due to this delay, there has not been possible to test two technologies at the moment. That means it is not possible to compare LTE-V with any other technology such as ITS-G5 in the same conditions. Testing is also affected by the number of units, that significantly influence the number of tested scenarios. Due to the limited time devoted to this master thesis and the very high costs of the units, there is not any other possibility, how to improve testing in a better way.

4.1.1 Used equipment

During the test, two vehicles were used. Both of the vehicles were equipped by:

- GPS locator,
- Antenna,
- C-V2X unit (QC-V2X-00005),
- Laptop,
- Charger,
- Cables.

The GPS locator and antenna were installed on the roof of vehicles as it is shown on the following picture (Figure 13). This antenna is named as the combined vehicle rooftop antenna provided by company Commsignia. The installation process was pretty simple with possibility of mag-mount as well as surface-mount. Due to the fact, that measuring took only few hours, magnetic mounting for temporary set-ups was used.

Figure 13: Antenna and GPS locator on the roof of the vehicle.

One antenna case is equipped with 4 antennas inside – it is noticeable due to the number of cables leading from the housing. It provides high performance of several use cases such as cellular GSM or GPS. The antenna should be mounted to a metal surface or ground plane to ensure the best performance.

Antenna and GPS locator were connected to the C-V2X unit provided by Qualcomm company, which was used as an interconnection to the laptop, to ensure control over the transmission and capturing of the packets / messages.

Figure 14: Inside vehicle equipment.

4.1.2 Testing procedure

As is written in the introduction of the chapter, specifically in the beginning of the Testing methodology, the measuring of technology LTE-V was affected by several technical issues. This subchapter tells the step-by-step story about the procedure of preparation and testing.

- Only 2 cars (two units) were available,
- Only 3 people were participated on the test,
- The test needed to have two people on the board (1 driver, 1 attendant responsible for the work on the laptop),
- Only one technology (LTE-V) was available,
- Radio parameter measurement was not available,
- Knowledge about telecommunication environment was missing (possibility of being influenced by noise around),
- No experience with the units, testing was considered to be as a "pre-pilot" measuring.

The testing was limited by the mentioned circumstances a lot. One vehicle had to be used only as a stationary object because of the lack of drivers – in each vehicle had to be at least one person, who served the computer. Due to the lack of other technologies such as ITS-G5 is not possible to compare them in the same environmental circumstances. The environment could influence the measurement in some way. We haven't been able to evaluate the degree of influence, because radio parameters were not be measured. The measurement was made at the first time outside from the lab. We decided to make the test outside of the city, because of the higher probability of correct measurement and less traffic around.

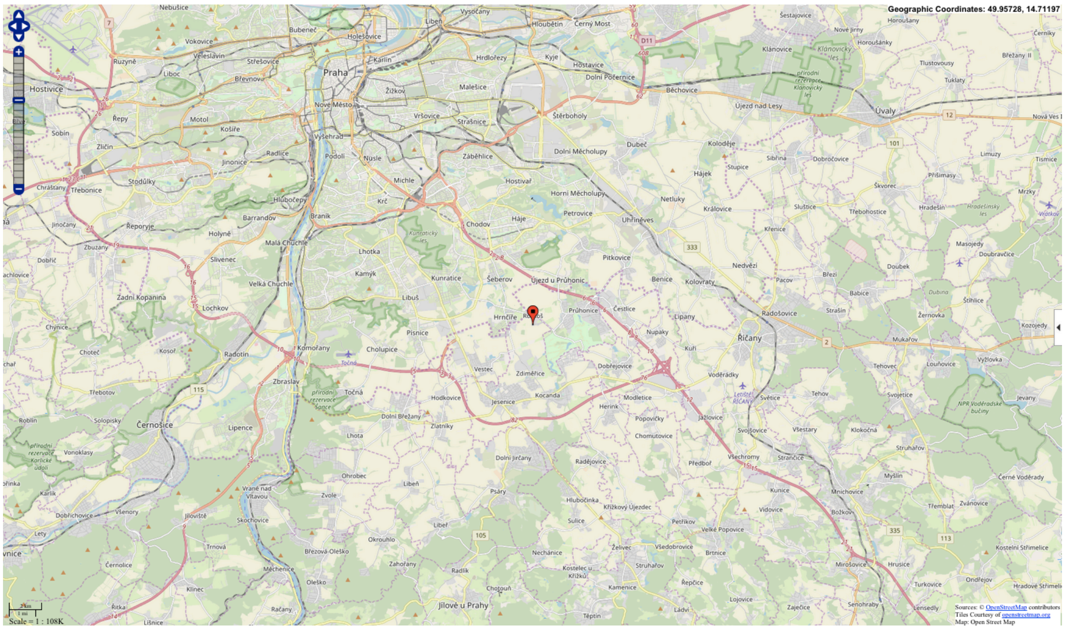


Figure 15: Place of the testing - Rozkoš. [49]

The location of the testing was close to the village Rozkoš, which is situated on the edge of Prague and Central Bohemian Region (See the Figure 15). The test was performed on a dirt road, without any other cars. It allowed the driving at very low speed (less than 30 kmph), which guarantee a high number of the measurements (sent messages). As is written above, during the whole test, one vehicle was staying in the same position and the second vehicle was going around. Both vehicles were sending CAM (Cooperative Awareness message) and DENM (Decentralized Environmental Notification Message) messages and also receiving them from each other.

The test contained two routes, where the non-stationary unit was going. This procedure was repeated three times with a different length of the message. The length of the messages was changed only at one unit, on the second (stationary) one was predefined fixed length. The length of DENM message in the first round was 1640 bytes, of the second one was 1274 bytes and the third one 726 bytes. On the stationary unit, the fixed length was set up at 1640 bytes all the time. As it follows, there were 6 different measurements.

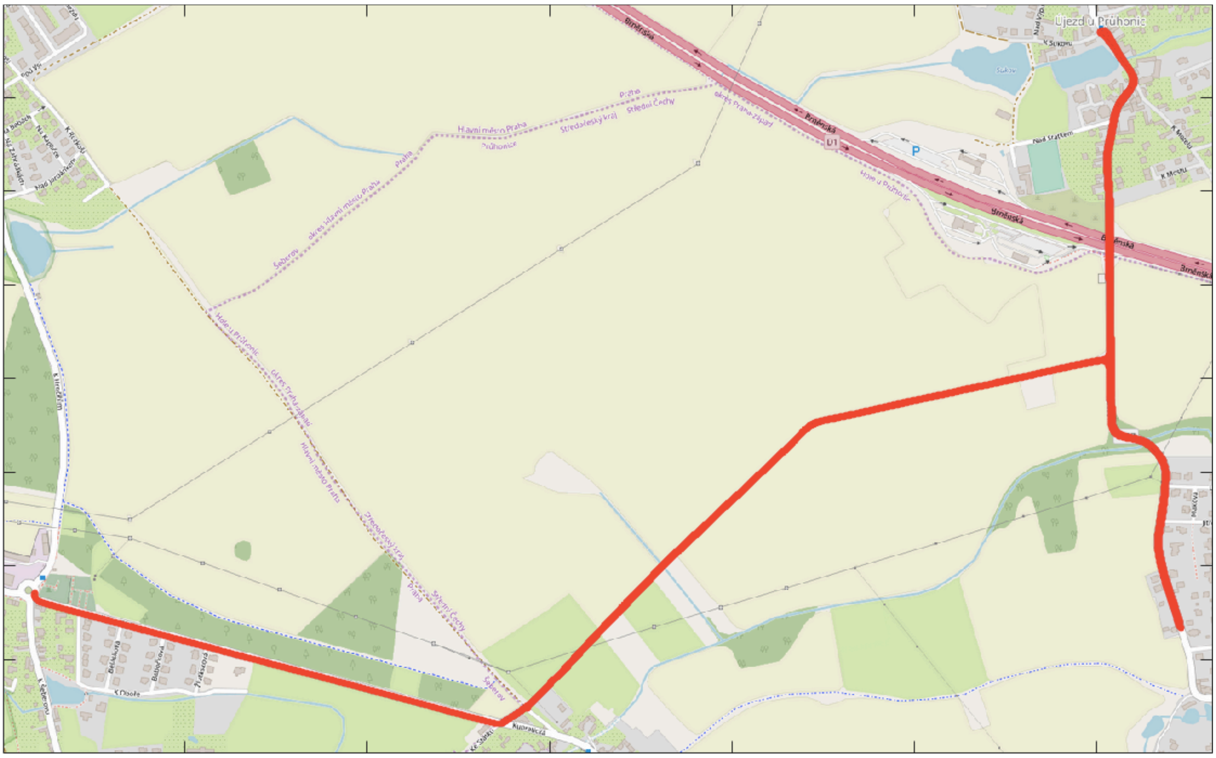
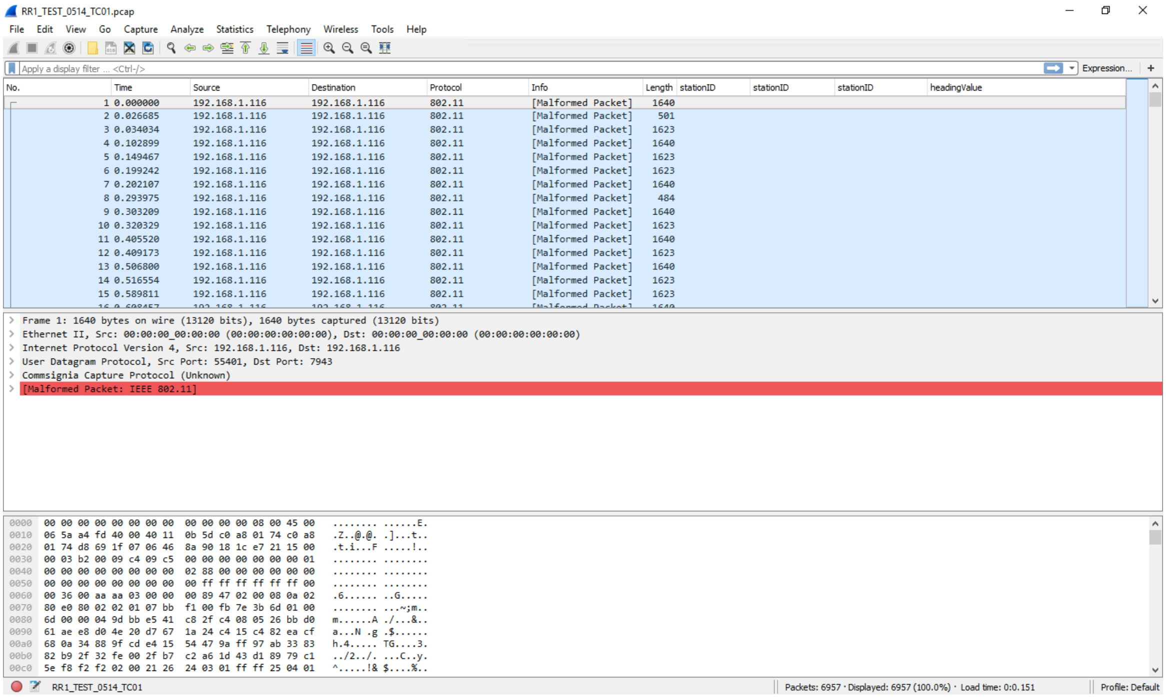


Figure 16: Tested route.

The aim of the test was to try to get LTE-V technology up and running, send and receive messages from the other vehicle. There was not tested a specific use-case of C-ITS because the main goal of this (first) measuring was to make the technology to work and observe a possible coverage.

4.1.3 Output from the measuring

The output from the measuring are logs from each vehicle (6 measurements from each vehicle). The expected format was a .pcap file, that is possible to analyze in a SW Wireshark and with SW tool, which is owned by faculty of transportation sciences.



```
No.     Time        Source          Destination     Protocol   Info                Length  stationID  stationID  stationID  headingValue
      1 0.000000    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1640
      2 0.026685    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]     501
      3 0.034034    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1623
      4 0.102899    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1640
      5 0.149467    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1623
      6 0.199242    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1623
      7 0.202107    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1640
      8 0.293975    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]     484
      9 0.303209    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1640
     10 0.320329    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1623
     11 0.405520    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1640
     12 0.409173    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1623
     13 0.506800    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1640
     14 0.516554    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1623
     15 0.589811    192.168.1.116   192.168.1.116   802.11     [Malformed Packet]    1623
```

```
> Frame 1: 1640 bytes on wire (13120 bits), 1640 bytes captured (13120 bits)
> Ethernet II, Src: 00:00:00_00:00:00 (00:00:00:00:00:00), Dst: 00:00:00_00:00:00 (00:00:00:00:00:00)
> Internet Protocol Version 4, Src: 192.168.1.116, Dst: 192.168.1.116
> User Datagram Protocol, Src Port: 55401, Dst Port: 7943
> Commsignia Capture Protocol (Unknown)
> [Malformed Packet: IEEE 802.11]
```

```
0000  00 00 00 00 00 00 00 00  00 00 00 00 08 00 45 00   ........ ......E.
0010  06 5a a4 fd 40 00 40 11  0b 5d c0 a8 01 74 c0 a8   .Z..@.@. .]...t..
0020  01 74 d8 69 1f 07 06 46  8a 90 18 1c e7 21 15 00   .t.i...F .....!..
0030  00 03 b2 00 09 c4 09 c5  00 00 00 00 00 00 00 01   ........ ........
0040  00 00 00 00 00 00 00 00  02 88 00 00 00 00 00 00   ........ ........
0050  00 00 00 00 00 00 00 00  00 ff ff ff ff ff ff 00   ........ ........
0060  00 36 00 aa aa 03 00 00  00 89 47 02 00 08 0a 02   .6...... ..G.....
0070  80 e0 80 02 02 01 07 bb  f1 00 fb 7e 3b 6d 01 00   ........ ...~;m..
0080  6d 00 00 04 9d bb e5 41  c8 2f c4 08 05 26 bb d0   m......A ./...&..
0090  61 ae e8 d0 4e 20 d7 67  1a 24 c4 15 c4 82 ea cf   a...N .g .$......
00a0  68 0a 34 88 9f cd e4 15  54 47 9a ff 97 ab 33 83   h.4..... TG....3.
00b0  82 b9 2f 32 fe 00 2f b7  c2 a6 1d 43 d1 89 79 c1   ../2../. ...C..y.
00c0  5e f8 f2 f2 02 00 21 26  24 03 01 ff ff 25 04 01   ^.....!& $....%..
```

Figure 17: Error message in the SW Wireshark.

As is shown on the previous page, on the Figure 17, the logs are secured, and it is not possible to analyze it by Wireshark (also by mentioned tool, that uses Wireshark). All of the packets are evaluated as a malformed packet. For analysis is necessary to have a special plug-in, which provides access to go in depth of the messages. Due to this problem the owner of the units provided a text file, which contains for example the GPS positions, station ID and other parameters for each specific message from the log. All of the data should be processed, because of its format.

4.2 Evaluation methodology

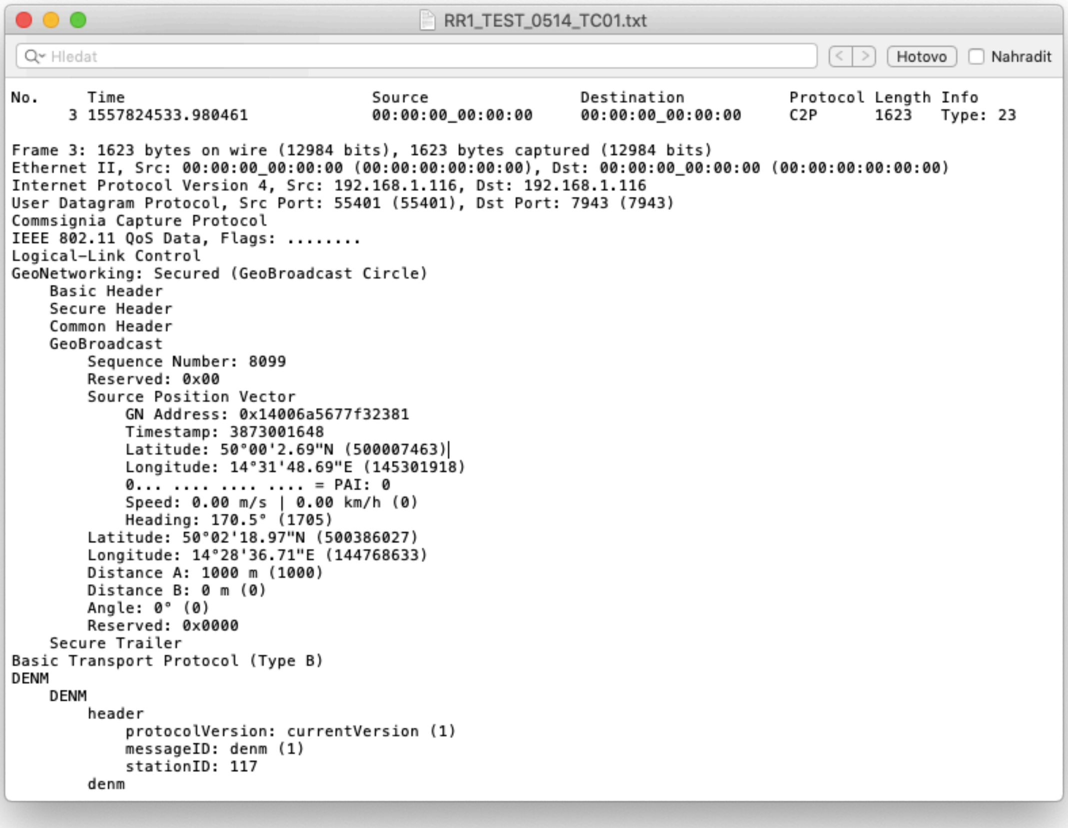
Based on the fact, that the output from testing is not in the format, that is commonly used, the data should be processed first. The evaluation is divided into the part of raw data processing and structured data acquisition, the second part is devoted to the evaluation itself.

4.2.1 Structured data acquisition

The raw data contains a wide range of parameters, such as number of the message, epoch time, length of the message, destination and source...etc.

Although the message looks full of the information at first glance (see Figure 18), these parameters are not valuable at all. Some of them have set the value to 0. In terms of the thesis, some of the parameters are not valuable at all.

The first step of the data processing procedure was to take a look on the exported text file from the log. It was necessary to find important parameters useful for evaluation and visualization. Thousands of messages were contained in the log (text file), in terms of it, the manual data process was not possible especially due to the consumption of time and effectiveness. The text files had to be processed by using computer technology. Due to the automatic procedure the checking of the text file structure is required. Within the raw data processing, the SW Matlab was used. Based on the mentioned steps the code had to follow the structure of messages and find each specific parameter.



```
No.     Time                           Source                Destination           Protocol Length Info
      3 1557824533.980461              00:00:00_00:00:00     00:00:00_00:00:00     C2P      1623   Type: 23

Frame 3: 1623 bytes on wire (12984 bits), 1623 bytes captured (12984 bits)
Ethernet II, Src: 00:00:00_00:00:00 (00:00:00:00:00:00), Dst: 00:00:00_00:00:00 (00:00:00:00:00:00)
Internet Protocol Version 4, Src: 192.168.1.116, Dst: 192.168.1.116
User Datagram Protocol, Src Port: 55401 (55401), Dst Port: 7943 (7943)
Commsignia Capture Protocol
IEEE 802.11 QoS Data, Flags: ........
Logical-Link Control
GeoNetworking: Secured (GeoBroadcast Circle)
    Basic Header
    Secure Header
    Common Header
    GeoBroadcast
        Sequence Number: 8099
        Reserved: 0x00
        Source Position Vector
            GN Address: 0x14006a5677f32381
            Timestamp: 3873001648
            Latitude: 50°00'2.69"N (500007463)
            Longitude: 14°31'48.69"E (145301918)
            0... .... .... .... = PAI: 0
            Speed: 0.00 m/s | 0.00 km/h (0)
            Heading: 170.5° (1705)
        Latitude: 50°02'18.97"N (500386027)
        Longitude: 14°28'36.71"E (144768633)
        Distance A: 1000 m (1000)
        Distance B: 0 m (0)
        Angle: 0° (0)
        Reserved: 0x0000
    Secure Trailer
Basic Transport Protocol (Type B)
DENM
    DENM
        header
            protocolVersion: currentVersion (1)
            messageID: denm (1)
            stationID: 117
        denm
```

Figure 18: Example of the DENM message in text format.

The script is written to find GPS location (Latitude, Longitude) in accordance with station ID and message ID. During the script writing, was necessary to keep in mind that the structure of CAM messages is a little bit different than the DENM messages structure. One log contains two different station ID's (116 – "going vehicle"; 117 – "waiting vehicle"), which is also important to implement in the code. In the going vehicle's log, the message with station ID 116 represents the sent message and 117 is the received message from the waiting vehicle. On the other hand, in the log of the waiting vehicle, the station ID 116 signifies the received message and 117 represents the sent. The script is attached in the Annex as a Matlab code.

Firstly, the script opens the text file, then goes through the file and looks for the station ID's. Based on the parameter with station ID, two entities are created. These entities define the sent and the received messages. Then the script asks if the message type is DENM or CAM. Depending on the message type two parameters are found – Latitude and Longitude. From these parameters the content of the brackets is loaded. The GPS position is expressed without decimal point, so the script adds it to the right position. The result is the creation of two arrays that contain GPS position (Latitude, Longitude) for all of the sent and received messages.

The same procedure for the time acquisition is followed. The main issue is that the time expressed by epoch time (also known as unix time) is in the same line as other 6 parameters. The advantage is that all of the parameters are written separately. It is necessary to use these gaps between values as a delimiter and bring the right value from the line. The result of this function is the time for each message from the log in seconds (epoch time) with satisfactory amount of decimal numbers.

4.2.2 Evaluation of the data

After the first data processing and acquisition of structured data was desirable to make an evaluation of the data and determine the results as a final output of the thesis. These determined data were reproduced in the numbers as well as in the graphs and other types of visualization.

In this subchapter is briefly overviewed, how the results occurred, and which approach has been used for evaluation as well as for visualization.

Distance calculation

Distance calculation between two points requires that each of the points has to contain GPS coordinates – one latitude value and one longitude value. These coordinates should be expressed in degrees only. Subdivision of the degree should be defined by using of decimal degrees not minutes nor seconds.

Firstly, the angle distance is calculated, which is represented by very small number – in decimal degrees. Then the decimal degrees are recalculated to the distance represented by kilometers and finally the distance in kilometers is converted to meters.

Due to the fact, that units for distance representation are very small – hundreds of meters in comparison to earth radius equal to thousands of kilometers, this calculation is simplified, based on the assumption, that the radius is independent on the degrees and the surface in the tested area is everywhere the same.

Received/sent packets ratio[4]

The calculation of packets ratio was based on the evaluation of two outputs from measuring. As previously written, one log from measuring contains two types of information – firstly all of the sent packets and secondly all of the received packets from the other units. So, it was required to evaluate at least two logs from the same measurement. According to the measured data, there are no other units around and the evaluation can be simplified (in the log were only station IDs of receiving and sending units).

In the packet ratio calculation were used GPS coordinates as well as time units of all the sent messages from one log based on the station ID and all of the received messages (with the same station ID) from the second log. This approach shows the total cumulative number of transmitted messages over the time until the specific distance (generally the maximal transmission distance) or specific time (difference between first and last received message) is reached.

Previously mentioned distance calculation is used for distance rating.

---

[4] Based on the fact, that the purpose of the test was to go with one vehicle far from the other (out of coverage) to measure maximal transmission distance, is necessary to mention that the total ratio could not be equal to 100%.

Mapping

The visualization of the sent (received) messages in the map is based on the GPS coordinates. The map itself is made as a picture by clipping from the OpenStreetMaps[5]. The picture of the map does not contain GPS coordinates, but pixels only. It is necessary to know the GPS coordinates of that picture – specifically left up and right down corner. All of the points expressed by GPS should be transformed to the pixels of the picture.

Transform function recalculates the difference between GPS coordinates and allocates coordinates expressed by pixels. The first step of the function is to load the picture. When the picture is uploaded in the Matlab, the size of the picture is calculated (expressed by pixels). The edges (GPS coordinates of left up and right down corner) should be manually set as the reference points. The last step of the function is to load the GPS coordinates, which have to be shown in the map (on the picture). The loaded data are recalculated based on the size of map (picture) and get back with pixel coordinates.

The map visualization is plotted like any other image or picture and points are figured as in a standard graph.

Sending (receiving) frequency

The frequency of messages is calculated by using of the time. The epoch time has to be converted to the time of measuring. This calculation is based on the difference with the first sent / received message. Then number of messages over each second is calculated.

---

[5] The OpenStreetMaps is a map portal available on: [49]

While the packet ratio is calculated over the whole time (in cumulative numbers) of measuring this method calculates continuously measured values for the specific interval (second). This provides more specific information about the number of sent or received messages during per one second. This information can be used for more detailed analysis to see at which time the receiving of the messages worked well and when not.

The same procedure can be applied in terms of the distance (number of messages per 10meters), not time.

4.3 Verification

Distance

Distance calculation was manually verified by using GPS distance calculator[6] and using the measuring of direct distance in the Google maps[7].

The sample of distance calculated via Matlab code between two points was stated as 232.11 meters, while distance based on the GPS distance calculator was 232.06 meters. The difference between these two measurements is insignificant for the purposes of the thesis.As the second tool for verification was used measurement in the Google maps, where the distance between the same points was calculated as 232.12 meters. The same conclusion can be stated – the difference is only few centimeters for this long distance, which is insignificant for the purposes of the thesis.

For correctly made verification, the next additional samples were used for comparison of calculated distance. These measurements are expressed on the following Table 1

---

[6] GPS distance calculator provides the calculation of distance based on the GPS coordinates, this calculator is available on: [50]

[7] Google maps is the map portal available on: [51]

Table 1: Distance [m] verification.

MATLAB Calculation	GPS distance calculator	Google Maps
232.11	232.06	232.12
477.99	477.66	477.15
132.33	132.30	132.34
419.76	419.50	419.74
1028.08	1027.40	1030*
927.87	927.27	927.88

Marked value (*) in the measurements shows that direct distance measuring via Google maps longer than 1km is not available in the decimal units (centimeters) and with high probability the value is also rounded up to the tens of meters.

Based on these measurements and observed accuracy of the calculated distance in comparison with GPS distance calculator and google maps direct distance measuring, the maximal errors in the calculation should be no longer than 1 meter. For the purpose of the thesis the distance is used only for information and this possible error (around 50 centimeters for the length 1km) does not affected the evaluation. The probable accuracy in meter units is satisfying. Finally, the distance calculation is stated as verified.

Mapping

The map verification was made manually. The GPS coordinates were used for visualization in Google maps as well as in the Matlab visualization. The comparison of the shown points in the maps was satisfying. All of the tested points were reproduced in the same position as in the Google maps. For the purposes of the thesis, the transform function together with map visualization were stated as verified.

Packets ratio & Sending frequency

Due to the fact that the messages do not contained any specific parameter, the correct verification has not been done. These calculated values are verified only based on the checking and comparison of the values represented in the maps. With assumption that mapping is correct (previously verified) is possible to at least make an inspection over the data.

These calculated data are not verified, but at least checked.

5 Results

Within the chapter results, wide range of graphs and visualizations has been done. Some of them are mentioned and described in the following text and figures.

Course of data exchange.

The first output from the measuring is mentioned on the Figure 19: Course of sent/received packet. is shown. This picture provides the brief overview, how many messages had been sent or received during the test, and also the first information about the coverage can be observed.

The picture shows that coverage was around 400 meters and it was tested almost on the 2 kilometers long distance. This picture provides information only about one measurement. It was based on the comparison of captured messages in the log from going and standing vehicle.

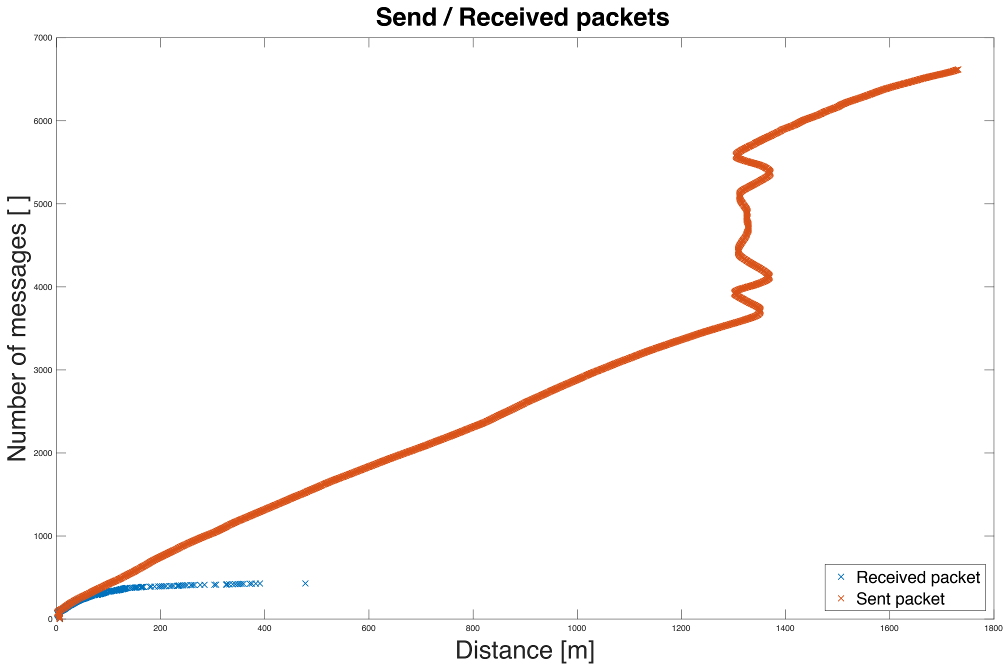


Figure 19: Course of sent/received packet.

On the distance around 1300m is observable that the course of sending messages grows rapidly in terms of message number, while distance is relatively fixed (oscillated between 1300 and 1400m). This phenomenon is caused by the chosen route of the vehicle at direct distance 1300m, the vehicle turned and "rode around the circle". That is why number of sent messages is still growing and direct distance is similar.

Previous visualization in detail

The following figure shows the detailed course in first 400meters. It is expressed by cumulative numbers (that is the reason why, sent packets are still growing). After a few tens of meters, the number of received packets is going to stop.

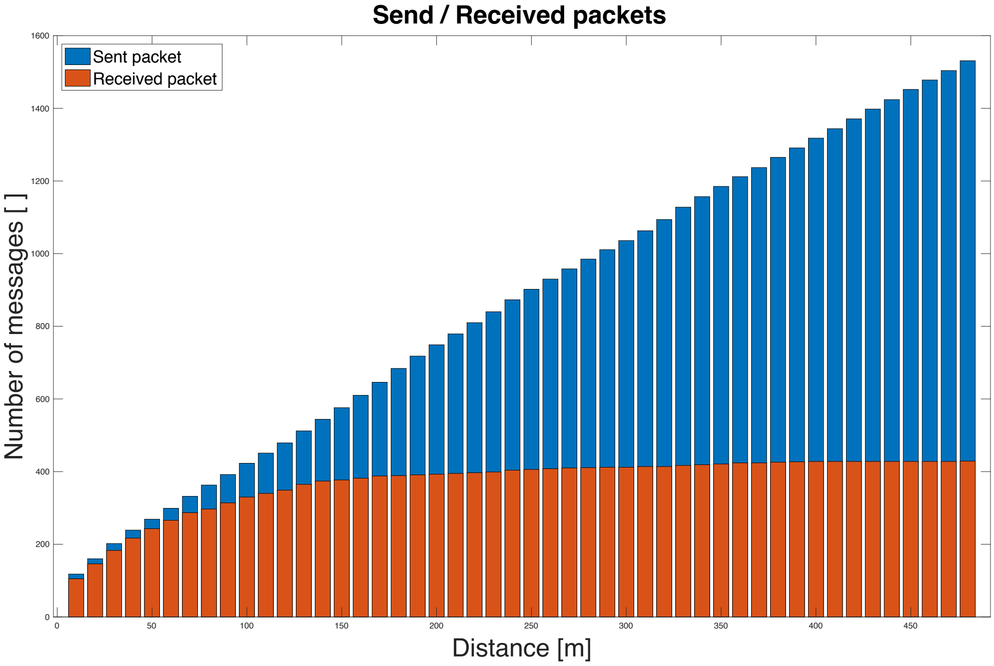


Figure 20: Cumulative number of sent and received messages.

It is possible to observe, that reliable communication is not on the long distance, but only up to tens of meters.

Received packets

Next visualization shows the received packets in terms of distance. The Figure 21: Packet capturing) shows the correctly received messages expressed by percentage. The reliability 80% received messages in only for the distance less than

50meters. That fact that coverage can be in hundreds of meters is important to mentioned that reliability decreases rapidly.

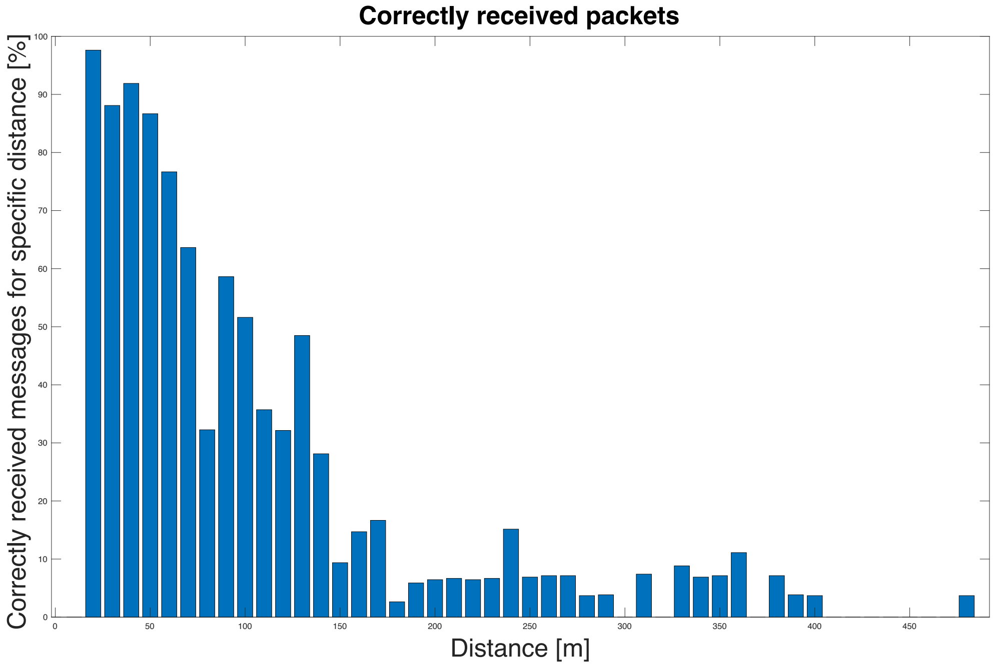


Figure 21: Packet capturing

The next graph shows almost the same but expressed by total numbers not by ratio.

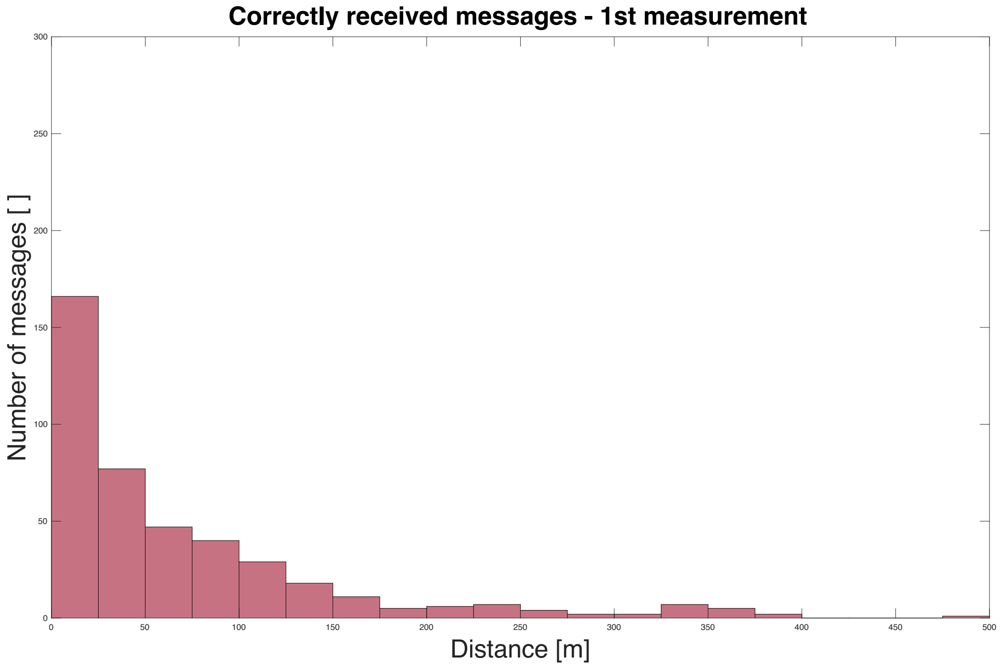


Figure 22: Packet capturing

Received messages according to the distance

The following graphs shows the course of messages in terms of distance. It is observable, that 3 mentioned transmissions have different course. It can be affected by the speed of vehicle (especially start of the vehicle). It is questionable, if the packet length could influence the transmission rate or if any issues happened during the test.

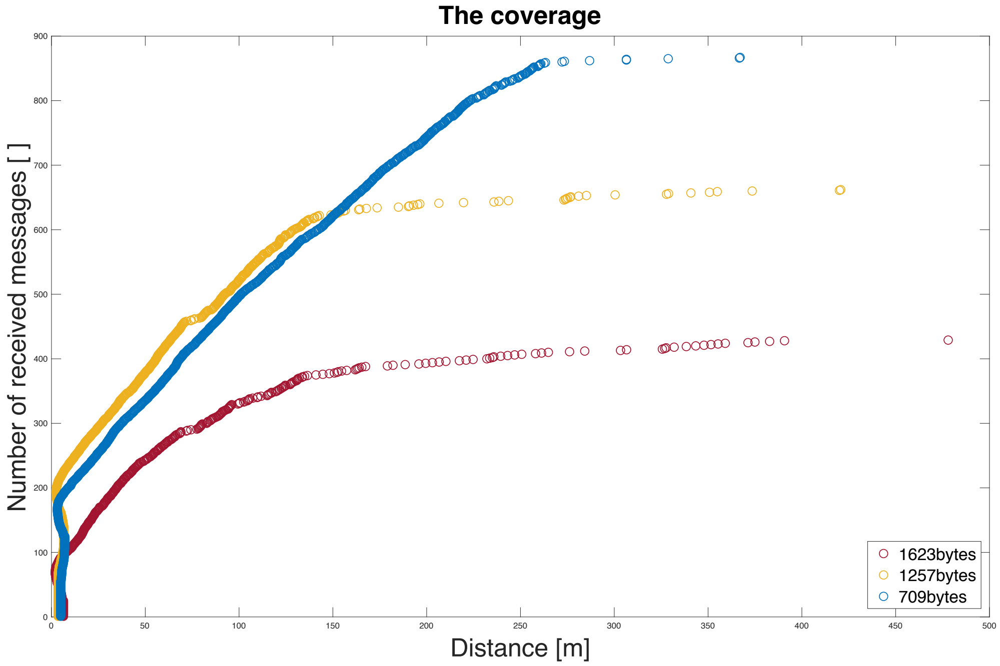


Figure 23: course of message receiving in total numbers.

Map visualization

The next picture shows from which position, the messages were received (all red points). These marked messages are showing all of the received messages over the whole testing (very high amount of the samples) from going vehicle, while blue dot represents the location of standing vehicle (receiver).

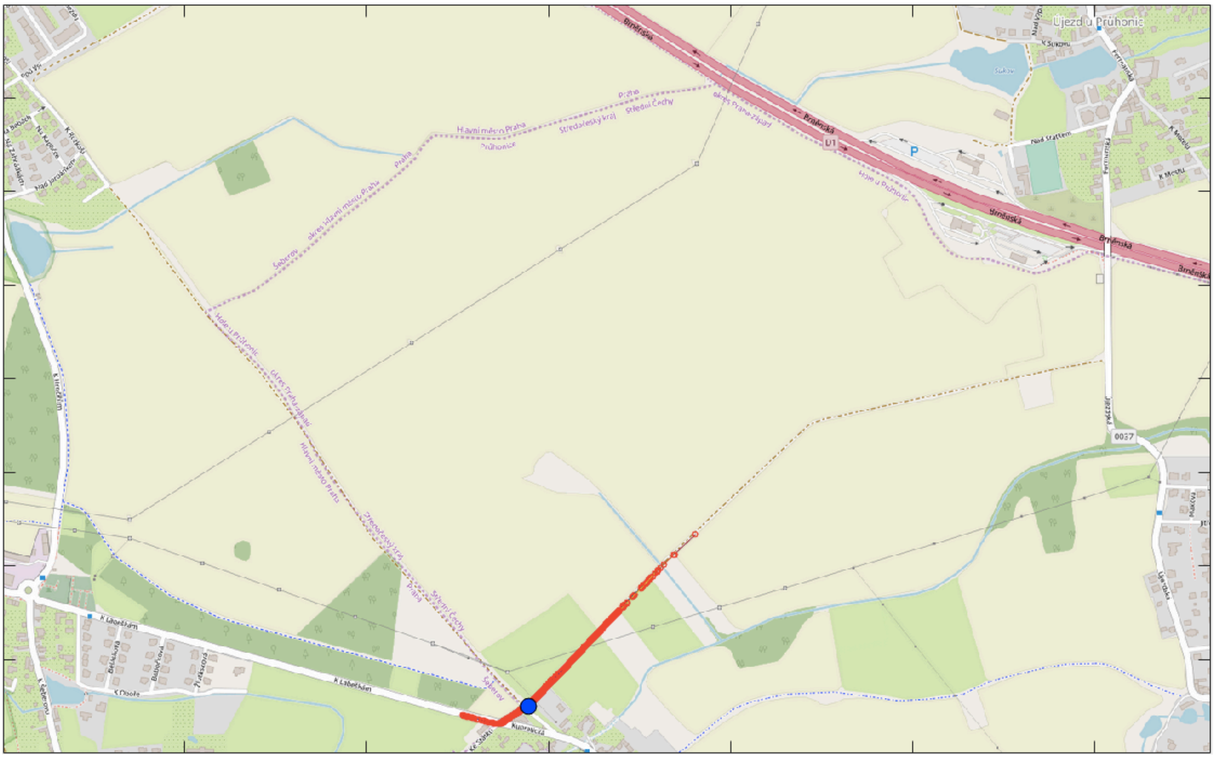


Figure 24: All of the received messages during the tests.

From this picture is observable that line of sight is the most significant influence during the whole measuring. As you can see, on north-east direction from the standing vehicle are longer distance reached (no obstacles, buildings...), while the west direction is really affected by the hence and bushes around.

The hence on the west direction made a border that avoids transmission of the data. All of the received data from that direction are exactly from the same position – in the map pretty close to dark green area. Compared to that, the received data from north-east direction are more "spread" along the road.

Receiving data in terms of time

Course of sent and received data is observable on the first picture. The second picture provides an overview how many packets were received during the time.

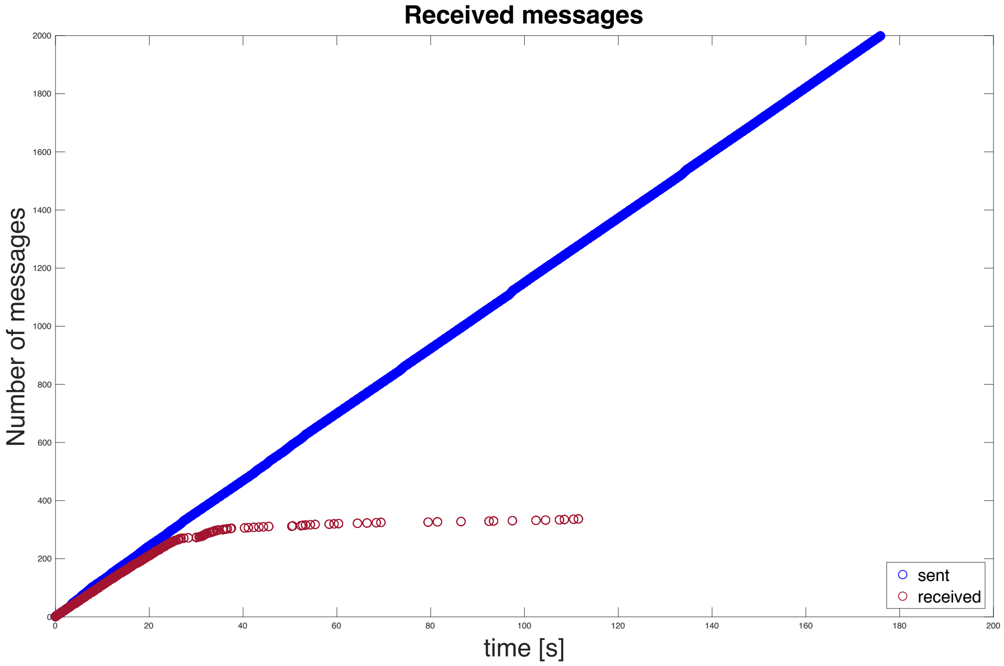


Figure 25: Sent and received messages over the time.

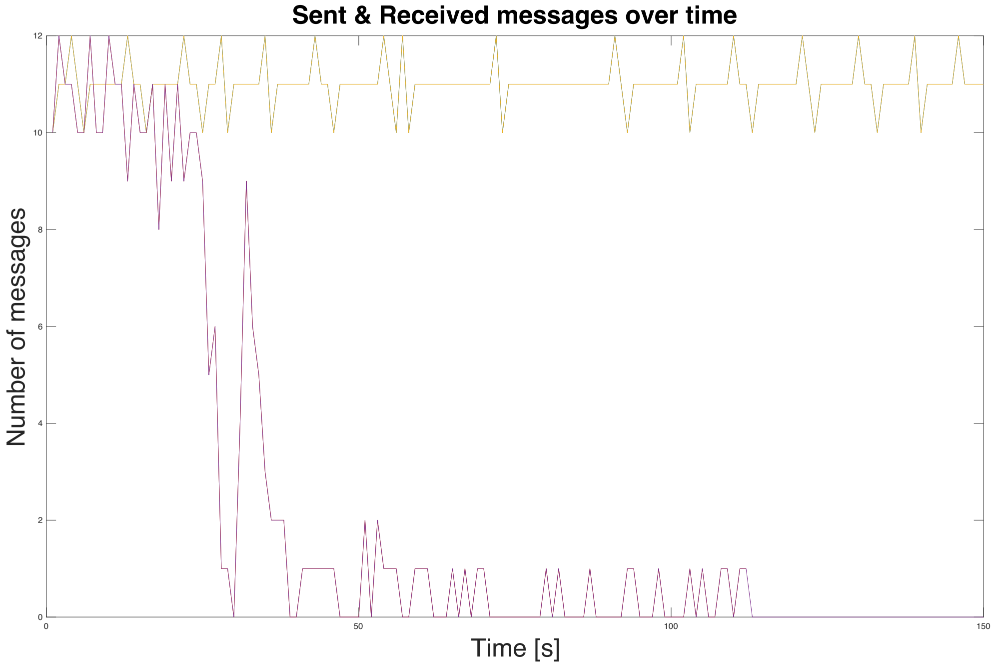


Figure 26: Course of packet sending and receiving.

Comparison of received data based on the unit

The last visualization provides the comparison of received data in terms of the unit of capturing. Despite the fact, that the same equipment was used during the test, the reception of the packets was different on each vehicle unit.

The captured packets in the standing vehicle were received from the longer distance as opposed to packets captured in the going vehicle. This can be affected by the position of antenna, but also because of other unexpected circumstances.

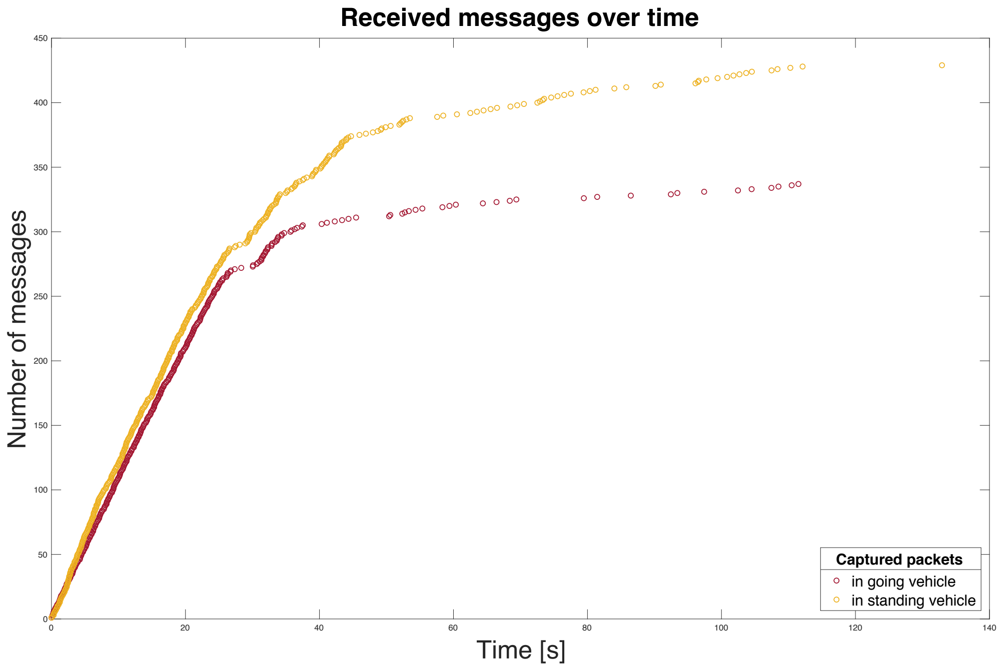


Figure 27: Packet reception over the time.

Conclusions

Final chapter of the thesis is devoted to the final overview, discussion, recapitulation, recommendations and future outlook.

5.1 Discussion

Firstly, it is important to discuss that field of C-ITS is relatively new and rapidly evolving. It means that spectacular technology, that seems as the best solution for today would not be suitable also for upcoming years. This fact should be still kept in our minds and it is really necessary to look forward into the future. The C-ITS are in a fast development and deploying of these systems has already started worldwide. In previous chapter mentioned technologies plays the key role in transportation and it seems that usage of C-ITS will grow intensively, because it is the way to future transportation according to several discussion about autonomous cars. These systems provide complementary solution, that can help these autonomous vehicles to be used.

As is mentioned, this field is rapidly growing and evolving in that case lot of the references that have been used are based on the expert articles, not books. The main reason is that fact sheets, test evaluation, results from trials and development can be more valuable for the purpose of the research than written books.

The usage of C-ITS will be probably growing, what we are not able to expect is the usage of specific technology. That has been the purpose of this thesis to look at relatively new technology, that can be used as an alternative to other technologies especially in Europe, where ITS-G5 is already in implementation.

This thesis brings further experiences, based on the testing. The testing has not fulfilled expectations completely, but at least particularly. The performed measurement showed, it is necessary to continue with the testing and trials, used knowledge from the last time and try to test not only coverage, but also try to find the way of testing specific scenarios, that can happened in normal traffic conditions to each driver.

The results from the test probably shows that the usage of technology LTE-V is on direct distance without any obstacles (line of sight distance). The test was very simple and was used as a “pre-trial” test, so it could be affected by several circumstances that has to be found in the next phases. Maybe, the future measurements will show different outputs.

Testing of LTE-V can be improved certainly, the location can be chosen in the better way without any obstacles, more units can be tested, different speeds etc. Due to the delays within the project related to this thesis, these improvements should be done in the future. Due to the strictly defined deadline of the thesis submission, these enhancements have not been worked in.

The previously estimated coverage around 1 kilometer (based on the research), has not been working. The data were sent on the distance around half a kilometer. The testing on the racetrack for example, where the line of sight is much longer, can bring better results. But for sure, it is necessary to keep in mind that cars going on the roads are not still in the perfect condition and some issues can be there. The testing in the city can bring very different results and the coverage should decrease rapidly.

Finally, LTE-V has not been tested within the thesis with other technologies, because of delays in tendering and installation of the units. All of the parameters can be affected in the scenario, where other technology (working on the similar frequency) will be applied.

5.2 Recapitulation

In summary, within the thesis, the analysis of C-ITS has been done not only in Czech Republic and Europe, but also worldwide. The analysis of telecommunication technologies, that can be used in C-ITS has been done with main focus on LTE-V technology. The test of this technology has been done with some outputs, but also with assumption that is necessary to continue with the tests. The methodology of testing has been prepared, but it is recommended to take into the consideration the outputs from the test and propose new methodology in a better way. The test of LTE-V has been evaluated and also verified.

As the author of this thesis I have gained a lot of experiences and I would like to continue with the research as well as with the testing in the project out of scope from this thesis.

5.3 Future outlook

As is proposed many times previously, it is necessary to follow new objectives and prepare new tests, new methodology, new evaluation and verification and come up with new results.

From this reason, some of the improvements and recommendations are written below:

- Radio parameters measurement,
- Other technologies during the test,
- More units, more drivers,
- Testing not only outside from the city, but in the city also.

When the next testing will be occurred, it will be very good to implement at least these recommended points. The radio parameters can bring new possibilities to improve installation and position of the antenna on the car could be also improved, maybe different part of the vehicle is more suitable. These measurements of radio parameters would bring new questions that should be answered. Maybe transmit power can be also improved or directional antenna can provide better results.

During the next measuring is recommended also to use other technologies as ITS-G5. Would be the results same? Would interference be there? That are also questions, that should be answered. The ITS-G5 may influence the measuring a lot.

What about more units? Would it be better to have more cars around? Will be the driver in the vehicle more informed in terms of higher amount of information? Maybe only delay will be occurred.

Was the tested area suitable? Isn’t better to test these technologies in real traffic condition? What about line of sight? What about city centers? How the technology works there? In the city center much more obstacles are between the vehicles and direct communication could be difficult.

All of these questions should be answered, and this is the way, how to improve the testing itself. It is necessary to keep in mind also different circumstances as user acceptance, costs and other.

References

[1] Centrum dopravního výzkumu, v. v. i., "Centrum dopravního výzkumu," Centrum dopravního výzkumu, v. v. i., 2019. [Online]. Available: https://www.cdv.cz/kooperativni-systemy-v-doprave/. [Accessed 2 May 2019].

[2] CAR 2 CAR Communication Consortium, "CAR 2 CAR Communication Consortium," CAR 2 CAR Communication Consortium, 2019. [Online]. Available: https://www.car-2-car.org/about-c-its/. [Accessed 2 May 2019].

[3] Z. Lokaj, HABILITAČNÍ PRÁCE: Návrh a úprava kooperativních systémů na základě vlivu systémových parametrů na jejich fungování, Praha: ČVUT, fakulta dopravní, 2014.

[4] X. Wu, R. Miucic, S. Yang, S. Al-Stouhi, J. Misener, S. Bai and W.-h. Chan, "Cooperative Connected Vehicles," 2018. [Online]. Available: http://ccv.eng.wayne.edu/reference/Cars%20Talk%20to%20Phones.pdf. [Accessed 4 May 2019].

[5] Bezpečnost silničního provozu, "BESIP," BESIP, 2019. [Online]. Available: https://www.ibesip.cz/Statistiky/Statistiky-nehodovosti-v-Ceske-republice/Dopravni-nehodovost-v-roce-2015/Chodci. [Accessed 20 April 2019].

[6] 5G Americas, "5G Americas V2X Cellular Solutions," G5 Americas, 2016. [Online]. Available: http://www.5gamericas.org/files/2914/7769/1296/5GA_V2X_Report_FINAL_for_upload.pdf. [Accessed 13 May 2019].

[7] Tampa Hillsborough Expressway Authority, "THEA Connected Vehicle Pilot," Tampa Hillsborough Expressway Authority, 2018. [Online]. Available:

https://www.tampacvpilot.com/wp-content/uploads/2018/11/2672-THEA-Connected-Vehicle-Pilot-Fact-Sheet-20181114-rgb.pdf. [Accessed 7 May 2019].

[8] The City of New York, "NYC Connected Vehicle Project For Safer Transportation," The City of New York, 2019. [Online]. Available: https://www.cvp.nyc/cv-safety-apps. [Accessed 7 May 2019].

[9] U.S. Department of Transportation, "Intelligent Transportation Systems Joint Program Office," U.S. Department of Transportation, 2019. [Online]. Available: https://www.its.dot.gov/factsheets/pdf/NYCCVPliot_Factsheet_020817.pdf. [Accessed 6 May 2019].

[10] The City of New York, "NYC Connected Vehicle Project For Safer Transportation," 2019. [Online]. Available: https://www.cvp.nyc/project-status. [Accessed 5 May 2019].

[11] Transport for New South Wales, "NSW Government - Transport for NSW Centre for Road Safety," Transport for New South Wales, 6 November 2018. [Online]. Available: https://roadsafety.transport.nsw.gov.au/research/roadsafetytechnology/cits/citi/index.html. [Accessed 5 May 2019].

[12] Transport for New South Wales, "NSW Government - Transport for NSW Centre for Road Safety," Transport for New South Wales, 6 November 2018. [Online]. Available: https://roadsafety.transport.nsw.gov.au/downloads/citi-overview.pdf. [Accessed 5 May 2019].

[13] 5GAA - 5G Automotive Association e.V., "5GAA," 5GAA - 5G Automotive Association e.V., 2019. [Online]. Available: http://5gaa.org/wp-content/uploads/2018/07/5GAA_WhitePaper_ITS-spectrum-utilization-in-the-Asia-Pacific-Region_FINAL_160718docx.pdf. [Accessed 5 May 2019].

[14] Telstra, "Telstra," Telstra, 2019. [Online]. Available: https://www.telstra.com.au/content/dam/tcom/about-us/investors/pdf%20F/Annual-Report-2017.PDF. [Accessed 4 May 2019].

[15] Telstra, "Telstra Exchange," Telstra, 2019. [Online]. Available: https://exchange.telstra.com.au/australia-moves-another-step-closer-to-driverless-vehicles/. [Accessed 4 May 2019].

[16] Cohda Wireless, "Cohda Wireless," Cohda Wireless, 2019. [Online]. Available: https://cohdawireless.com/telstra-4g-trial/. [Accessed 8 May 2019].

[17] Ministry of Land, Infrastructure and Transport & Korea Expressway Corporation, "C-ITS," Ministry of Land, Infrastructure and Transport & Korea Expressway Corporation, 2019. [Online]. Available: https://www.c-its.kr/english/service.do. [Accessed 8 May 2019].

[18] Ministry of Land, Infrastructure and Transport & Korea Expressway Corporation, "C-ITS," Ministry of Land, Infrastructure and Transport & Korea Expressway Corporation, 2019. [Online]. Available: https://www.c-its.kr/english/history.do. [Accessed 8 May 2019].

[19] SCOOP Project : connected road and vehicle, "Project SCOOP," SCOOP Project : connected road and vehicle, 4 April 2019. [Online]. Available: http://www.scoop.developpement-durable.gouv.fr/en/general-presentation-a9.html. [Accessed 10 May 2019].

[20] Norwegian Public Roads Administration, "Nordic WAY 2," Norwegian Public Roads Administration, 2019. [Online]. Available: https://www.nordicway.net . [Accessed 10 May 2019].

[21] A. Fagerholt, "NordicWay Architecture," 2019. [Online]. Available: https://uploads-ssl.webflow.com/5c487d8f7febe4125879c2d8/5c5c02e041f53910b5d9de64_NordicWay%20Demo_architecture%20slides.pdf. [Accessed 10 May 2019].

[22] NordicWay, "Deployment Roadmap Recommendations for future work," 19 December 2017. [Online]. Available: https://uploads-ssl.webflow.com/5c487d8f7febe4125879c2d8/5c5c02aed70742869390395a_NordicWay%20Roadmap%20M_12%20(secured).pdf. [Accessed 10 May 2019].

[23] Talking Traffic, "Traffic Talking," Talking Traffic, 2019. [Online]. Available: https://www.talking-traffic.com/en/talking-traffic/the-partnership. [Accessed 6 May 2019].

[24] Government of the Netherlands, "Government of the Netherlands," 21 March 2018. [Online]. Available: https://www.government.nl/latest/news/2018/03/21/first-talking-traffic-services-live-for-traffic-users. [Accessed 6 May 2019].

[25] Talking Traffic, "Talking Traffic," Talking Traffic, 2019. [Online]. Available: https://www.talking-traffic.com/en/whats-in-it-for. [Accessed 8 May 2019].

[26] Talking Traffic, "Talking Traffic," 2019. [Online]. Available: https://www.talking-traffic.com/images/Documenten/TT-Brochure.pdf. [Accessed 8 May 2019].

[27] The Austrian contribution to the Cooperative ITS Corridor, "ECo-AT," The Austrian contribution to the Cooperative ITS Corridor, 2019. [Online]. Available: http://www.eco-at.info/facts-and-figures.html. [Accessed 11 May 2019].

[28] K&S GmbH Projektmanagement, "Cooperative ITS Corridor," K&S GmbH Projektmanagement, 2019. [Online]. Available: http://www.c-its-korridor.de/?menuId=42&sp=en. [Accessed 11 May 2019].

[29] Amsterdam Group, "AMSTERDAM GROUP," Amsterdam Group, 2019. [Online]. Available: https://amsterdamgroup.mett.nl/Corridor+initiatives/default.aspx . [Accessed 10 May 2019].

[30] InterCor, "InterCor," InterCor, 2019. [Online]. Available: https://intercor-project.eu. [Accessed 10 May 2019].

[31] InterCor, "InterCor," InterCor, 2019. [Online]. Available: https://intercor-project.eu/homepage/c-roads/. [Accessed 10 May 2019].

[32] C-ROADS, "C-ROADS," C-ROADS, 2019. [Online]. Available: https://www.c-roads.eu/platform.html. [Accessed 9 May 2019].

[33] C-ROADS, "C-ROADS," C-ROADS, 2019. [Online]. Available: https://www.c-roads.eu/pilots/core-members.html. [Accessed 9 May 2019].

[34] C-ROADS Czech Republic, "C-ROADS," C-ROADS, 2019. [Online]. Available: https://c-roads.cz/?page_id=1603. [Accessed 9 May 2019].

[35] C-ROADS, "C-ROADS," C-ROADS, 2019. [Online]. Available: https://www.c-roads.eu/pilots/core-members/czech-republic/Partner/project/show/c-roads-czech-republic.html. [Accessed 9 May 2019].

[36] C-ROADS, "C-ROADS," 2019. [Online]. Available: https://www.c-roads.eu/fileadmin/_processed_/9/2/csm_Czech_Republic_pilot_site_698c11d844.png. [Accessed 9 May 2019].

[37] C-ROAD Czech Republic, "C-ROADS," C-ROADS, 2019. [Online]. Available: https://c-roads.cz/?page_id=1566. [Accessed 9 May 2019].

[38] Český kosmický portál, "Český kosmický portál," Český kosmický portál, 2019. [Online]. Available: http://www.czechspaceportal.cz/4-sekce/veda-a-vyzkum/vybrane-aktuality-a-clanky-3/inteligentni-dopravni-systemy-v-akci---pilotni-testovani-projektu-basic.html. [Accessed 15 May 2019].

[39] EUROPEAN COMMISSION, COMMISSION DELEGATED REGULATION (EU) of 13.3.2019 supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the deployment and operational use of cooperative intelligent transport systems, Brussels: EU, 2019.

[40] EUROPEAN COMMISSION, Commission Delegated Regulation supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the deployment and operational use of cooperative intelligent transport systems, Brussels: EU, 2019.

[41] EUROPEAN COMMISSION, "European Commission," 2019. [Online]. Available: https://ec.europa.eu/info/law/better-regulation/feedback/18167/attachment/090166e5c12a3443_en. [Accessed 2 May 2019].

[42] Cadillac PRESSROOM, "Cadillac PRESSROOM," Cadillac PRESSROOM, 2019. [Online]. Available: https://media.cadillac.com/media/us/en/cadillac/news.detail.html/content/Pages/news/us/en/2017/mar/0309-v2v.html. [Accessed 9 May 2019].

[43] CAR 2 CAR Communication Consortium, "CAR 2 CAR Communication Consortium," CAR 2 CAR Communication Consortium, 2019. [Online]. Available: https://www.car-2-car.org/press-media/press-releases/press-

details/?tx_news_pi1%5Bnews%5D=7&tx_news_pi1%5Bcontroller%5D=News &tx_news_pi1%5Baction%5D=detail. [Accessed 11 May 2019].

[44] 3GPP, "3GPP A GLOBAL INITIATIVE," 3GPP, 2019. [Online]. Available: https://www.3gpp.org/technologies/keywords-acronyms/98-lte. [Accessed 11 May 2019].

[45] 3GPP, "3GPP A GLOBAL INITIATIVE," 3GPP, 2019. [Online]. Available: https://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced. [Accessed 12 May 2019].

[46] 5GAA - 5G Automotive Association e.V., "5GAA," 5GAA - 5G Automotive Association e.V., 2019. [Online]. Available: http://5gaa.org/news/5gaa-releases-updated-white-paper-on-c-v2x-deployment-timeline/. [Accessed 7 May 2019].

[47] 3GPP, "3GPP A GLOBAL INITIATIVE," 2019. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/21_series/21.914/. [Accessed 10 May 2019].

[48] R. Molina-Masegosa and J. Gozalvez, "LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications," *IEEE Vehicular Technology Magazine,* vol. 12, no. 4, pp. 30-39, 2017.

[49] Open Street Maps, "Open Street Maps," Open Street Maps, 2019. [Online]. Available: https://www.openstreetmap.org/. [Accessed 20 May 2019].

[50] CSG Network, "CSG Network," CSG, Computer Support Group, Inc. and CSGNetwork.Com, 2019. [Online]. Available: http://www.csgnetwork.com/gpsdistcalc.html. [Accessed 20 May 2019].

[51] Google Maps, "Google Maps," Google, 2019. [Online]. Available: https://www.google.com/maps. [Accessed 20 May 2019].

List of figures

Figure 1: Thesis outline. 10

Figure 2: V2V communication. 13

Figure 3: V2I and I2V communication. 13

Figure 4: V2P communication. 14

Figure 5: V2N communication. 15

Figure 6: Current status of the project. [10] 16

Figure 7: Core members of project C-Roads. [33] 20

Figure 8: C-Roads deployment in Czech Republic. [36] 21

Figure 9: LTE-V communication interfaces. [47] 25

Figure 10: V2V indirect communication over LTE-Uu interface. 27

Figure 11: Network managed communication over PC5 in cell. coverage. 30

Figure 12: Self-managed communication over PC5 out of cell. coverage. 31

Figure 13: Antenna and GPS locator on the roof of the vehicle. 33

Figure 14: Inside vehicle equipment. 34

Figure 15: Place of the testing - Rozkoš. [49] 35

Figure 16: Tested route. 36

Figure 17: Error message in the SW Wireshark. 37

Figure 18: Example of the DENM message in text format. 39

Figure 19: Course of sent/received packet. 46

Figure 20: Cumulative number of sent and received messages 47

Figure 21: Packet capturing 48

Figure 22: Packet capturing 48

Figure 23: course of message receiving in total numbers. 49

Figure 24: All of the received messages during the tests. 50

Figure 25: Sent and received messages over the time. 51

Figure 26: Course of packet sending and receiving. 51

Figure 27: Packet reception over the time. 52

List of tables

Table 1: Distance [m] verification. 44

Annex

- CD with pdf file
- Matlab codes
- Text files with data