

**CZECH TECHNICAL UNIVERSITY IN PRAGUE**  
**FACULTY OF TRANSPORTATION SCIENCES**  
**&**  
**FACHHOCHSCHULE TECHNIKUM WIEN**



Bc. Pavel Matějka

**METHODOLOGY FOR VERIFYING  
CHARACTERISTICS OF COOPERATIVE SYSTEMS IN  
A REAL WORLD**

Master's Thesis

**Prague 2016**



**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. Pavel Matějka**

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

**N 3710 – IS – Intelligent Transport Systems**

Theme title (in Czech): **Metodika ověřování vlastností kooperativních systémů v reálném prostředí**

Theme title (in English): Methodology for Verifying Characteristics of Cooperative Systems in a Real World

### **Guides for elaboration**

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

- Analyze different types of cooperative systems and implemented pilot projects in the Czech Republic and Europe.
- Analyze valid and upcoming ISO, CEN and ETSI standards related to cooperative systems, especially their verification
- Analyze used approaches to verification characteristics of cooperative systems and describe monitored parameters
- Design methodology for verification qualitative and quantitative characteristics of cooperative systems within the project Opponent's review of cooperative systems in CZ pilot project
- Realize validation according to the proposed methodology in a real environment
- Perform an evaluation of the measured results of the validation and determine conclusions.

Graphical work range: 10 pictures

Accompanying report length: minimal 55 pages

Bibliography: Zelinka, T., Svítek, M.: Telekomunikační řešení pro  
informační systémy síťových odvětví, Grada 2009  
Svoboda, J.: Telekomunikační technika, Sdělovací  
technika 2002  
Specialized journals  
Internet

Master's thesis supervisor: **FH-Prof. DI Harald Wahl**  
**doc. Ing. Pavel Hrubeš, Ph.D.**

Date of master's thesis assignment: **June 30, 2015**  
(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: **June 1, 2016**  
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



doc. Ing. Pavel Hrubeš, Ph.D.  
head of the Department  
of Transport Telematics



prof. Dr. Ing. Miroslav Svítek, dr. h. c.  
dean of the faculty

I confirm assumption of master's thesis assignment.



Bc. Pavel Matějka  
Student's name and signature

Prague ..... June 30, 2015

## Affidavit

I do not have a compelling reason against the use of this school work within the intention of s. 60 of the Act No. 121/2000 Coll., on Copyright and Rights Related to Copyright and on Amendment to Certain Acts (Copyright Act).

I declare that I have elaborated this thesis independently using information sources listed in the bibliography in accordance with Ethical guidelines for writing diploma theses.

Bc. Pavel Matějka



In Prague 25. 5. 2016

signature .....

## **Acknowledgements**

I would like to express the deepest appreciation to my supervisors and leaders of the project “Human and global communication”, Doc. Ing. Zdeněk Lokaj Ph.D and Ing. Martin Šrotýř, for their constant guidance and support through my whole study, without which this work would not have been possible.

I would like to thank my supervisor in Vienna, FH-Prof. DI Harald Wahl, who provided me support and advices during my study in Vienna and during writing my master’s thesis.

In addition, I wish to thank my friend Tomáš Jizba, for all the support, entertainment, comraderie and encouragement he provided me since elementary school.

And last but not least a thank to my mom, dad and grandparents for their love and unconditional support.

## **Abstract**

Author: Bc. Pavel Matějka

Name of master's thesis: Methodology for verifying characteristics of cooperative systems in a real world

School in CZE: Czech Technical University in Prague, Faculty of Transportation Sciences

School in AT: Fachhochschule Technikum Wien

Year of Publication: Prague 2016

Pages: 97

This master's thesis deals with the cooperative systems and methodology how to test their function and parameters. Thesis deals with the parts and transmission technologies and applications of cooperative systems. In addition in this thesis is an overview of European projects implemented in the area of cooperative systems. Also in this thesis we analyze the valid standards from the area of ITS, which we can use for the main part of the thesis, which is design of the methodology for testing of cooperative systems. Before the designing of the methodology we will write about methods of verification for cooperative systems and monitored parameters. The last part consists of a process of testing cooperative systems according to proposed methodology in a real world.

Key words:

C2X, C2C, C2I, Cooperative systems, OBU, RSU, ITS, Telecommunications, Testing, Methodology

# Contents

Affidavit .....	4
Acknowledgements.....	5
Abstract .....	6
List of used abbreviations .....	9
List of tables .....	11
List of graphs .....	11
List of figures .....	11
1. Introduction .....	13
1.1 Goal of the thesis .....	14
2. Introduction to cooperative systems .....	15
2.1 Parts of cooperative systems .....	17
2.2 Communication technology .....	18
2.2.1 IEEE 802.11p.....	18
2.2.2 DSRC .....	19
2.2.3 IEEE 802.16e .....	19
2.2.4 IEEE 802.20 .....	20
2.2.5 Mobile data networks – LTE A.....	20
2.3 Cooperative systems applications.....	20
2.4 Projects in the field of cooperative systems .....	21
2.4.1. SIM <sup>TD</sup> .....	22
2.4.2. COOPERS .....	24
2.4.3. Ecomove .....	26
2.4.4. Drive C2X .....	28
2.4.5. Compass4D .....	30
2.4.6. BaSIC.....	33
2.4.7. TE-VOGS .....	34
2.4.8. eCall.....	35
3. Standards.....	38
3.1 ISO .....	38
3.2 CEN .....	39
3.3 ETSI.....	39
3.4 C-ITS standards.....	39

3.4.1	C-ITS Architecture standards.....	40
3.4.2	C-ITS testing standards.....	50
4.	Verification of cooperative systems.....	54
4.1	Conformance.....	54
4.2	Interoperability .....	56
4.3	Performance indicators.....	57
4.3.1.	Telematics performance indicators.....	58
4.3.2.	Telecommunications performance indicators .....	61
5.	Methodology.....	64
5.1.	Physical layer tests .....	64
5.2.	Data link layer tests.....	66
5.3.	Network and transport layer tests .....	67
5.4.	Session, presentation and application layer testing .....	68
6.	Testing in a real world.....	71
6.1.	Testing location .....	71
6.2.	Testing equipment .....	73
6.3.	Tests .....	74
6.3.1.	Physical layer.....	74
6.3.2.	Data link layer.....	79
6.3.3.	Network and transport layer.....	79
6.3.4.	Session, presentation and application layer .....	79
6.4.	Results .....	89
6.4.1.	Physical layer tests .....	89
6.4.2.	Session, presentation and application layer tests.....	90
7.	Conclusion .....	92
7.1.	Future work and costs for testing .....	94
8.	References.....	95



## List of used abbreviations

<b>Abbreviation</b>	<b>English name</b>
AC	Access Categories
ADSL	Asymmetric Digital Subscriber Line
ASFINAG	Die Autobahnen- und Schnellstraßen-Finanzierungs Aktiengesellschaft
BSA	Basic Set of Applications
BTP	Basic Transport Protocol
CAM	Cooperative Awareness Message
CAN	Controller Areal Network
C2C	Car to Car
C2I	Car to Infrastructure
C2X	Car to X
CGW	Communication Gateway
CO <sub>2</sub>	Carbon Dioxide
COOPERS	Cooperative Systems for Intelligent Road Safety
CSC	COOPERS Control Centre
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CVIS	Cooperative vehicle – Infrastructure systems
CZE	Czech Republic
DENM	Decentralized Environmental Notification Message
DITCM	Dutch Integrated Test site for Cooperative Mobility
DSRC	Dedicated Short Range Communications
eCall	Emergency Call
Ecomove	Ecology Movement
EDCA	Enhanced Distribution Channel Access
EU	European Union
EUT	Equipment Under Test
FCD	Floating Car Data
FDD	Frequency Division Duplexing
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Groupe Spécial Mobile
HeERO	Harmonized eCall European Pilot
HMI	Human-Machine Interface
IEEE	Institute of Electrical and Electronics Engineers

ISM	Industrial, Scientific and Medical applications
ITS	Intelligent Transport System
IUT	Implementation Under Test
LAN	Local Area Network
LDM	Local Dynamic Map
LLC	Logical Link Control
LOS	Line of Sight
LTE	Long Term Evolution
LTE - A	Long Term Evolution – Advanced
MAC	Media Access Control
MAN	Metropolitan Area Network
MBWA	Mobile Broadband Wireless Access
MSD	Minimal Set of Data
NRZ	Non-Return to Zero
OBB	Österreich Bundes Bahn
OBE	On-Board Equipment
OBU	On-Board Unit
OFDM	Orthogonal Frequency Division Multiplexing
PC	Personal Computer
RHS	Road Hazard Signaling
RP	Reference Point
RSCP	Received Signal Code Power
RSE	Road-Side Equipment
RSSI	Received Signal Strength Indication
RSU	Road-Side Unit
Sevecom	Secure Vehicle Communication
Sim <sup>TD</sup>	Sichere Intelligente Mobilität – Testfeld Deutschland
SMS	Short Message Service
SP	Sub- project
STP	Shielded Twisted Pair
SUT	System Under Test
TCC	Traffic control center
TDD	Time Division Duplexing
TSS	Test Site Structure
UMTS	Universal Mobile Telecommunication System
US	United States
UTP	Un-Shielded Twisted Pair
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to X
WAVE	Wireless Access in Vehicular Environment
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

## List of tables

Tab. 1 - Content of MSD .....	37
Tab. 2- List of common facilities [34] .....	46
Tab. 3 - List of domain facilities [34] .....	46
Tab. 4 - Basic set of applications [38] .....	48
Tab. 5 - Tested IUTs in ITS .....	55
Tab. 6 - Influence of distance on RSSI and received packets .....	78
Tab. 7 - Packet analysis for Lexus .....	80
Tab. 8 - Packet analysis for Toyota .....	80

## List of graphs

Graph 1 - Histogram of max. transmission distances for Toyota .....	75
Graph 2 - Histogram of max. transmission distances for Lexus .....	76
Graph 3 - Influence of distance on RSSI and received packets .....	78

## List of figures

Fig. 1 - Penetration of vehicles on the future market [2] .....	15
Fig. 2 - Test locations of project SimTD [5] .....	22
Fig. 3 - Architecture of the SimTD OBU [5] .....	23
Fig. 4 - Elements of COOPERS system [9] .....	25
Fig. 5 - Test locations of COOPERS project [9] .....	26
Fig. 6 - Architecture of Ecomove system [10] .....	28
Fig. 7 - Test locations of project Drive C2X [11] .....	29
Fig. 8 - Test locations of project Compass4D [12] .....	31
Fig. 9 - Testing of application about movement of emergency vehicles [15] .....	34
Fig. 10 - Example of the HMI of TE-VOGS [14] .....	35
Fig. 11 - Scheme of eCall service [17] .....	37
Fig. 12 - Functional view on Decentralized congestion control [23] .....	40
Fig. 13 - Managing of multiple channels by Channel configuration entity [24] .....	41
Fig. 14 - ITS network architecture[29] .....	43
Fig. 15 - BTP packet structure [31] .....	44
Fig. 16 - Geographical areas[32] .....	44

Fig. 17 - Example of functional requirement for BSA [38] .....	49
Fig. 18 - Abstract protocol tester [42] .....	51
Fig. 19- Recommended SUT .....	56
Fig. 20 - Highway maintenance center Svojkovice .....	72
Fig. 21 - 50th and 57th km of D5 highway .....	72
Fig. 22 – Spectrometer during testing .....	73
Fig. 23 - Frequency allocation testing .....	74
Fig. 24 - Max. transmission distance in the map for Toyota .....	76
Fig. 25 - Max. transmission distance in the map for Lexus .....	77
Fig. 26 - RSSI in case of sender switched off (left) and switched on (right) .....	79
Fig. 27 - Damaged CAM packet .....	81
Fig. 28 - Complete CAM packet with errors .....	82
Fig. 29 - Complete CAM packet with few errors .....	84
Fig. 30 - Complete DENM packet .....	86
Fig. 31 - Complete CAM packet without errors.....	87

# 1. Introduction

Cooperative systems are systems based on interchange of data and information between vehicles themselves, vehicles and infrastructure and other devices. These systems, among others, significantly reduce time, in which the traffic information can be available to the drivers and increase quality and reliability of this information. Idea of cooperative systems is over 30 years<sup>1</sup> old but research was limited due to a lack of technical knowledge. Now the cooperative systems offer numerous applications from field of safety, infotainment, and traffic management and so on. Nowadays hinder the deployment of these systems to daily life large financial demands, time consuming standardization and development of norms for world-wide compatibility.

Main motivation for implementation of cooperative systems is increase of safety on the roads. Most of the traffic accidents with injured or dead people are caused by undisciplined or unexperienced drivers. The most common causes of accidents are incomplete dedication to driving (sending SMS messages, tuning the radio, phone calls etc.), speeding, not keeping a safe distance to next vehicle and not giving a priority to other vehicles. Most of the causes can be avoided by using cooperative systems. Other benefits include reduction of congestions (thereby reducing economic losses), shorter trip times, increase of road capacity and increase of effectivity of public transport.

The major steps in the completion of a typical cooperative system and his applications can be summarized into following four steps: design, implementation, testing and operation. All of these steps are equally important, but in my thesis we would like to focus mainly on the testing step. Testing of cooperative systems is a very demanding process. Unfortunately, for proper testing of cooperative systems is needed knowledge from numerous disciplines, e.g. telecommunications, programming or engineering. Testing of every Intelligent transport system (ITS) consist of two crucial parts, conformance testing and interoperability testing. Purpose of these two testing parts is developing a system that fulfills international standards and protocols, and also we must ensure that system can communicate with other systems or devices in a correct way.

Currently, there is a huge development of these systems, particularly through a number of European and global initiatives and activities that constitute the driving force in the development, standardization and implementation of cooperative systems in transport and spreading awareness of these systems among the general public. There are four big interest

---

<sup>1</sup> First project from field of cooperative systems was Wolfsburger Welle project (1981 - 1983), which deal with communication between vehicle and traffic lights equipped with communication node.

groups in cooperative systems: road operators (public authorities), car manufacturers, cellular network operators and users (drivers). In the process of standardization, road operators and car manufacturers are the most visible ones, because for them is implementation of cooperative systems business on the other hand for cellular network operators it means only increased costs (they have to invest in cellular network in order to increase coverage, availability and so on).

Target audiences for this master thesis are another technicians and engineers, who want to deepen their knowledge from field of ITS and cooperative systems and want to learn how cooperative systems can be evaluated with respect to standards. So we are expecting that technicians have basic knowledge of used terminology, so the technical expressions will be explained only briefly. For understanding of this master's thesis is required from the audiences basic knowledge from telecommunications (be familiar with terms like bandwidth, signal transmitting etc.), computer networks (networking, OSI model) and process of standardization. Everything else is explained enough that technician shouldn't have problem to understand other parts of the thesis.

## **1.1 Goal of the thesis**

Goal of the thesis is to summarize the issue of cooperative systems, their characteristics and reasons why we should equip every car with these systems in the future. In the thesis we would like to mention some crucial projects from the area of cooperative systems, who participate and what was done during these projects. Within these European projects were validated numerous standards, even about testing of cooperative systems, which will be also incorporated in the thesis. Next will be done analysis of used approaches to verification characteristics of cooperative systems, then we will be able to design methodology for verification characteristics, which will be done within the Opponent's review of cooperative systems in CZE pilot project. After that, we will validate the proposed methodology in a real environment and then evaluate the measured results.

## 2. Introduction to cooperative systems

Road transportation is very different from other modes of transport in numerous aspects. One of them is that on road we can find a lot of types of vehicles, from buses to bicycles. Another difference is that most of these vehicles are not driven by professionals, but amateurs with different level of driving skill and different age. Similarly technical condition of individual vehicles can be very different and also cost of purchasing and maintaining of vehicle is low unlike the railway or flight transport. In road transport thus occur a lot of incidents, which is necessary to process and manage in a real time. This information about incidents is necessary to distribute among other participants of road traffic, in form of recommendations. We are using for dissemination of information three basic types of communication:[1] [3][8] [18]:

- Vehicle - Vehicle

Communication Vehicle – Vehicle (V2V)<sup>2</sup> enables to vehicle communicate directly with another vehicle in his range. This kind of communication is used mainly for safety applications, where every millisecond can decide about consequences of incidents. Also it is used in places, where Road Side Unit (RSU) is not available (RSU could be out of order or physically missing). V2V communication is decentralized, thus it is not dependent on the backbone network. For this kind of communication is necessary to have minimum penetration of the vehicles equipped with cooperative systems in the road traffic. As the safety minimum penetration threshold is stated 10 %.

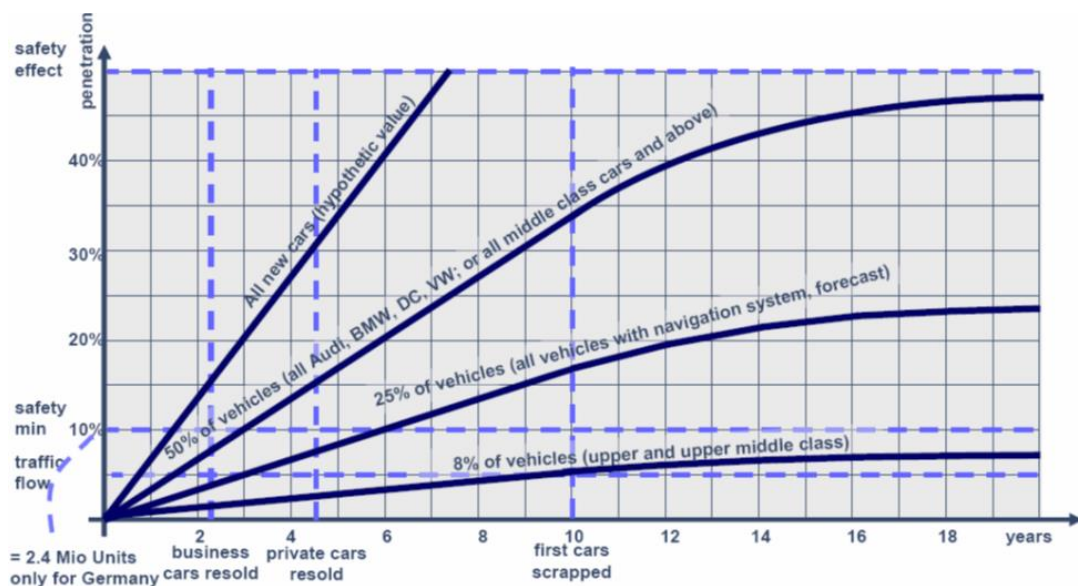


Fig. 1 - Penetration of vehicles on the future market [2]

<sup>2</sup> Some literature is using term Car – Car (C2C)

- Vehicle - Infrastructure  
Communication Vehicle – Infrastructure (V2I)<sup>3</sup> connects vehicle with the access points placed along the road and thus mediates the connection with the backbone network, on which are connected all communication nodes and therefore connection to the Ethernet network. This kind of communication is primarily used for effective management of the traffic flow, typical applications are warning before congestion, warning before road works etc. The most limiting factor in this kind of communication are the high costs for building the infrastructure along the road.
- Vehicle – X  
Communication Vehicle – X (V2X)<sup>4</sup>, where X is different type of communication device, other than the vehicle or communication node along the road, connects vehicle with mobile phones or tablets. There is a big potential in the area of entertainment and also in the area of safety, because most of the pedestrians are equipped with the mobile phones, which could be detected by vehicles in order to warn the driver before possible dangerous situations e.g. when pedestrian cross the road in the area, where driver cannot see. However this kind of communication is least tested and researched.

With these kinds of communications we transfer two types of messages [1]:

- One-time message  
One-time message informs the driver about the events caused by dangerous situations, e.g. critical vehicle braking or warning before obstacle on the road. It is therefore a local danger detected by vehicles and transferred via V2V communication.
- Repeated message  
Repeated message informs the driver about less dynamic events taking place before him. Typical example could be bad weather conditions on the road or restrictions on the road due the road works. For dissemination of this type of messages is in the most of the cases used V2I communication.

---

<sup>3</sup> Some literature is using term Car –Infrastructure (C2I)

<sup>4</sup> Some literature is using term Car –X (C2X)



## 2.1 Parts of cooperative systems

Every cooperative system consists of at least 3 basic parts, which have to properly communicate between each other. These parts are [18]:

- Traffic control center

Traffic center has important role in a cooperative systems, center has to collect, categorize, process and transfer huge amount of data. Data is collected by vehicles equipped with OBU, traffic detectors, communication nodes along road or meteorological stations. Based on these data, the traffic center manages and control traffic in the assigned area. Information derived from collected data is disseminated in form of recommendations to every traffic participant by telecommunication network, to which is communication nodes connected.

- OBU

OBU (On Board Unit) is communication and computational device placed in the vehicle. Task of the OBU is to obtain data from the internal vehicle's sensors, process it and transfer it to all vehicles and communication nodes within the range. Similarly, OBU has to receive the data from other vehicles. Is it obvious, that if we send messages from every vehicle to all vehicles in the vicinity, the OBU units would be overloaded by processing of the all incoming data, which can cause an unavailability of the OBU. There are ongoing tests in this area to find out which kind of filtering is the most effective. Another task is to transfer the information to the driver through HMI<sup>5</sup>.

- RSE (RSU)

RSE (Road Side Equipment) are parts of the cooperative systems situated along the roads. On the other hand RSU (road side unit) is the communication device itself. Task of these communication nodes is to wirelessly transmit data to OBU in vehicles. RSE can communicate with the traffic center by ethernet network. For the correct and effective operation of the cooperative systems is necessary to have sufficient coverage of the road by these communication units.

---

<sup>5</sup> HMI – Human Machine Interface

## 2.2 Communication technology

Generally, the telecommunication networks, which have to provide some kind of service, constitute of three basic parts:

- Network node equipment – it is used to provide services, it is information source (server) and connecting device (router, switch )
- Backbone network – it is used to transfer data between communication nodes in the network
- Access network – it is used to transfer data between communication nodes and users

Backbone network consist of connectors and nodes, connectors forms a physical transmission paths (nowadays connectors are mainly fiber optic cables). By using of WDM<sup>6</sup> backbone system we can achieve bandwidth capacity of up to tens of Tb/s. Access network provides connection to the user to the telecommunication network, in case of cooperative system it should be wireless network capable of establishing connection to the users during their movement. [4]

On the communication technologies for cooperative systems are placed high demands, mainly because one of their primary goals is to prevent dangerous situations endanger human. Among the requirements for the communication technology belong latency, bit rate, sufficient coverage, accuracy, reliability, availability and integrity. These requirements, plus the requirement on the mobility, are fulfilled by followings technologies. Currently, there is no technology, which is suitable for all applications of the cooperative systems. [16].

### 2.2.1 IEEE 802.11p

IEEE 802.11p is a standard from the IEEE 802.11 family. 802.11 standards are one of the most widely used wireless technologies of access networks on the market. They are so used because they operate in the unlicensed bands only on the basis of public authorization. The downside of this approach is that the unlicensed band is overcrowded and we can't guarantee quality of the service, that's why 802.11p works in the licensed band 5.9 GHz. IEEE 802.11p is designed for mobile devices (WAVE – Wireless Access in Vehicular Environment). The standard expands the 802.11 standards to support mobile telematics applications. The working group began to work on the standard in the 2004 and completed it in 2010. In 2010 this standard was also approved as a basis of ITS G5 technology. Currently

---

<sup>6</sup> WDM – Wavelength Division Multiplex

it is the most widely used technology for projects in the field of cooperative systems. The channel width is 10 MHz, compared to the typical 20 MHz for Wi-Fi technology, and this standard uses multiplexing method OFDM (Orthogonal Frequency Division Multiplexing), like the IEEE 802.16 or ADSL. Mobility is guaranteed up to 200 km/h and range is in units of kilometers. [6] [19]

### **2.2.2 DSRC**

DSRC is microwave technology specially developed for use in transport. It operates in the two bands 5.8 GHz (Europe and Japan) and 5.9 GHz (North America), both bands have their own set of standards and protocols, so devices operating in one band are not compatible with the devices operating in the second band. In Europe we can find DSRC at toll gates, the first electronic toll system based on this technology was launched in Austria in 2004. This technology is quite old, its standardization began in 1992 and ended in 1997 in North America and 1999 in Europe. DSRC advantage is low latency, climate resistance and high mobility (reported up to 250 km / h). The maximum theoretical transfer rate is 27 Mb/s (5.9 GHz), respectively. 20.48 Mb/s (5.8 GHz) which is sufficient for use in co-operative systems. [7]

### **2.2.3 IEEE 802.16e**

802.16e belongs between 802.16 standards, referred to as WiMAX (Worldwide Interoperability for Microwave Access). WiMAX working group was established in 1999, its goal was to create a standard for cheap and easily expandable wireless Internet access for MAN (Metropolitan Area Network - metropolitan area network). The first version of the standard was released in 2001 (802.16). 802.16e standard operates in the 2-6 GHz and offers transfer speeds up to 15 Mb / s, while enabling seamless connectivity at speeds up to 150 km / h. The theoretical range is up to 50 km in the field and 10 km in urban areas. 802.16e allows the use of two duplex schemes FDD (Frequency Division Duplexing) and TDD (Time Division Duplexing). Unfortunately, TDD wasn't allowed yet in the Czech Republic, so it can't operate there. [6]

#### **2.2.4 IEEE 802.20**

Standard 802.20 also known as MBWA (Mobile Broadband Wireless Access) was developed as wireless broadband interface for mobile devices. Developing took 6 years, from 2002 to 2008, but currently it is not being developed. MBWA can provide connectivity to the vehicles travelling by up to 250 km/h with asynchronous transmission speed (different speed of download and upload). It operates in the licensed 3.5 GHz band and can use channel width of 5 MHz, 10 MHz or 20 MHz. Similarly to standards IEEE 802.16 and IEEE 802.20, IEEE 802.20 allows using two duplex schemes, FDD and TDD. [18]

#### **2.2.5 Mobile data networks – LTE A**

As a representative of mobile data networks, I chose the latest technology in this field, LTE-A (Long Term Evolution - Advanced). LTE-A is built on the previous LTE technology, which has been developed since 2004 and the first commercial deployment was in 2009 (but back in 2009 LTE was still third generation network). As a fourth generation network, LTE-A has to meet the condition of transmission speed, specifically 1 Gb/s for stationary equipment and 100 Mb/s for mobile devices. LTE-A is able to seamlessly provide connectivity to devices with speed up to 350 km / h. LTE-A as well as LTE uses OFDM multiplex. The big advantage of LTE-A and other mobile networks is that the construction of the infrastructure for the transmission is done by telecom companies. Another advantage is their popularity among the population and large area coverage.[6]

### **2.3 Cooperative systems applications**

There are a lot of applications for cooperative systems on the market with different goals. According to their function, we can divide these applications into the following 6 categories: [18]

- **Safety applications**

Applications in this area are currently the most tested and analyzed. Their purpose is to warn the driver in critical situations and prevent accidents or at least reduce their consequences. Such applications include, for example, electronic brake lights, warning before an obstacle on the road, overtaking assistant, driving assistant at the intersection or warning about speeding.

- Traffic management applications

Applications for traffic management are designed to increase the efficiency of traffic flow control and thus prevent unnecessary delays on the trip in the form of congestions and waiting on intersections equipped with traffic lights. Examples of these applications can be dynamic allocation of lanes or Traffic information & Smart routing.

- Ecological applications

Goal of the ecological applications is to reduce fuel or energy consumption. These applications are working in two ways. First of them is to teach driver how to drive more efficient way e.g. by advising proper gear or recommending better route or even proper use of vehicle systems like air conditioning. Second way is to make traffic flow more uniform with the help of traffic management applications, because decelerating an accelerating again is one of the most increasing factors in the cities.

- Service applications

These applications are designed to improve vehicle maintenance; they use connection to a service center and information from internal sensors in the vehicle. Typical applications are remote calibration or service intervals watching.

- Applications for the entertainment

These applications are used to increase the comfort of the vehicle occupants. Applications use connection to the internet network and can offer to users e.g. interconnection with social networks, downloading audio and video files or video calls.

## **2.4 Projects in the field of cooperative systems**

Europe has already implemented several projects devoted primarily to C2C and C2I communication. In this chapter I deal with a few projects that take place in Europe especially Czech Republic. I chose projects that are in my opinion important for the progress in this area, whether in Europe or in the Czech context. Among other projects, which are not mentioned here, but also involved in the development include PReVENT, Safespot, SEVECOM, CVIS or ecoDriver.

### 2.4.1. SIM<sup>TD</sup>

SimTD<sup>7</sup> was a joint project of mainly German companies, with the participation of car manufacturers, suppliers of automotive components, telecommunications companies and scientific institutions. Main role in the project played primarily Daimler, Audi and BMW and telecommunications company Deutsche Telekom. The project was funded by the German Ministry and the Federal State of Hesse. The project began its activities in 2009 and ended after four years, in June 2013. The project was conceived from three different phases. The first phase was tasked to define the requirements for elements of cooperative systems and specify the function and architecture of the individual elements and equip the vehicle and infrastructure of prototypes of these systems. In the second phase, vehicles and infrastructure was equipped with the finished products and the first tests began, but just only between individual vehicles. Tests in a large number of participants, analysis of the tests and release of findings and recommendations were task of the third phase. SimTD tests took place in a real traffic around Frankfurt (Fig. 2) on highways and roads of all categories, but also in the very center of the city, in which was installed 24 communication nodes on traffic light's poles and these nodes collected data on roads every 200 – 500 meters.

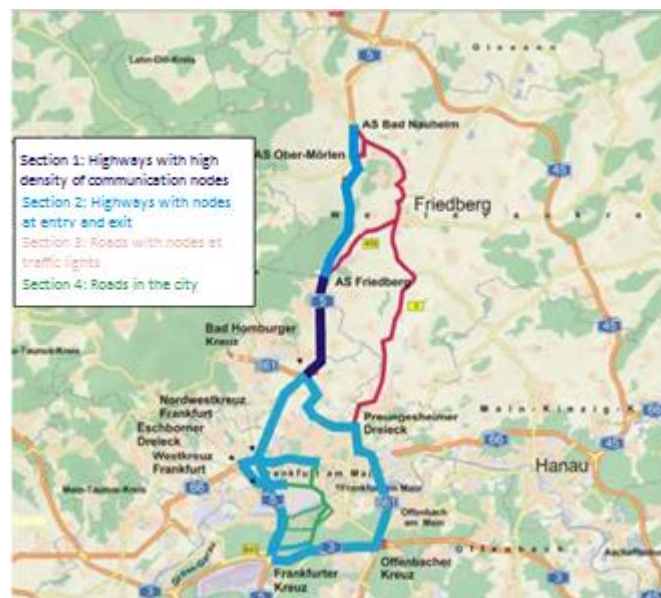


Fig. 2 - Test locations of project SimTD [5]

Test drivers had to fulfill specific driving scenarios. SimTD test center was located in the traffic management center of the federal state of Hesse. The center was gathering all the data from the SimTD system and merged them with other data from the traffic. Based on these data, management center sent recommendations to all vehicles in the field. These data

<sup>7</sup> Sim<sup>TD</sup> – From the German Sichere Intelligente Mobilität – Testfeld Deutschland

was also used by a traffic management center in Frankfurt am Main to manage traffic flow through the traffic lights and variable traffic signs. Researchers expected that during the collection, processing and verification was accumulated around 60 TB of data. The main objective of the project was to increase road safety and improve the efficiency of existing transport systems through communication between vehicles and between vehicles and infrastructure. Researchers wanted to achieve their goal by their own development and testing of OBU (Fig. 3), communication nodes and safety applications.

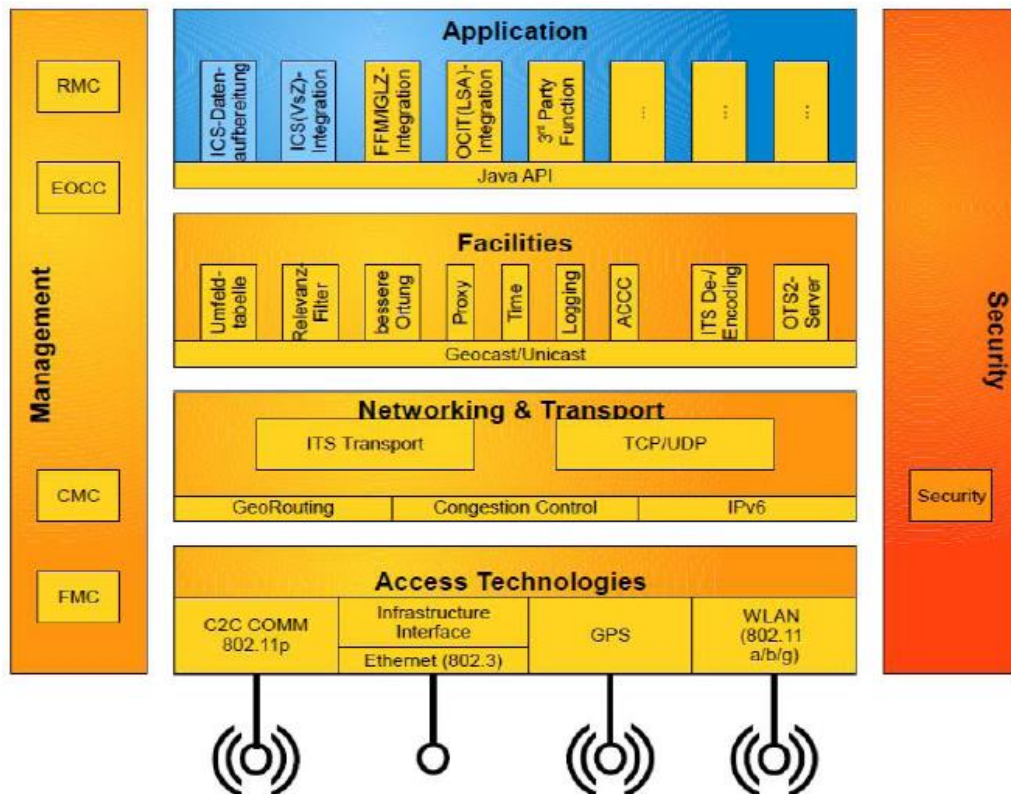


Fig. 3 - architecture of the SimTD OBU [5]

For testing purposes were along roads near Frankfurt built more than 100 communication nodes. In the testing participated 120 vehicles, which drove 41 000 hours in real traffic and 650 000 km. With these figures, SimTD was the biggest project, which took place in Europe. A total of 500 drivers between 23 to 65 years participated in tests. SimTD tests have shown that this technology actually leads to an increase in road safety and increase in efficiency. Thanks to the results of the project, scientists reveal that the number of accidents involving personal injury in Germany can be reduced from 288,297 in 2010 to nearly 200,000 in 2035. They also estimated that due to safety applications (monitoring of traffic signs, critical braking warning etc.) would save total 6,411 million Euros to 2035. Similarly, savings through efficiency enhancing applications for traffic flow are estimated about 4 900 million Euros. [5]

### 2.4.2. COOPERS

COOPERS<sup>8</sup> project ran from 2006 to 2010. The project was co-financed by the European Union (9.8 billion euros) and there were 40 other entities (eg. BMW, Ascom, SWARCO and Efkon), who put together a budget of 16.8 billion Euro. The aim of the project was to develop a cooperative transportation system, which linked vehicle and vehicles through wireless network, and test this system in operation. In this system, the data and information about vehicle's surroundings was exchanged between the entities. This system was designed to contribute to improvement of road safety and increase efficient of traffic management.

Developed system consists of following entities: (Fig. 4):

- TCC – Traffic control center: Task of TCC is to manage and control traffic. TCC sends traffic information to drivers and provides transport data through the network to COOPERS Service Center
- CSC – COOPERS Service Center: CSC receives and decodes traffic data from the Traffic Control Center, provides COOPERS service and sends messages using wireless technology
- RSU – Road Side Unit: Receives and transmits traffic data from and to the Traffic Control Center and to the traffic participants
- OBE – on-board equipment set
  - In-vehicle HMI: displays COOPERS services
  - CGW communication Gateway: transmits the message and sends Floating Car Data (FCD) to the Traffic Control Centre
  - Automotive PC: Control HMI receives and decodes COOPERS services

---

<sup>8</sup> COOPERS - Cooperative Systems for Intelligent Road Safety.



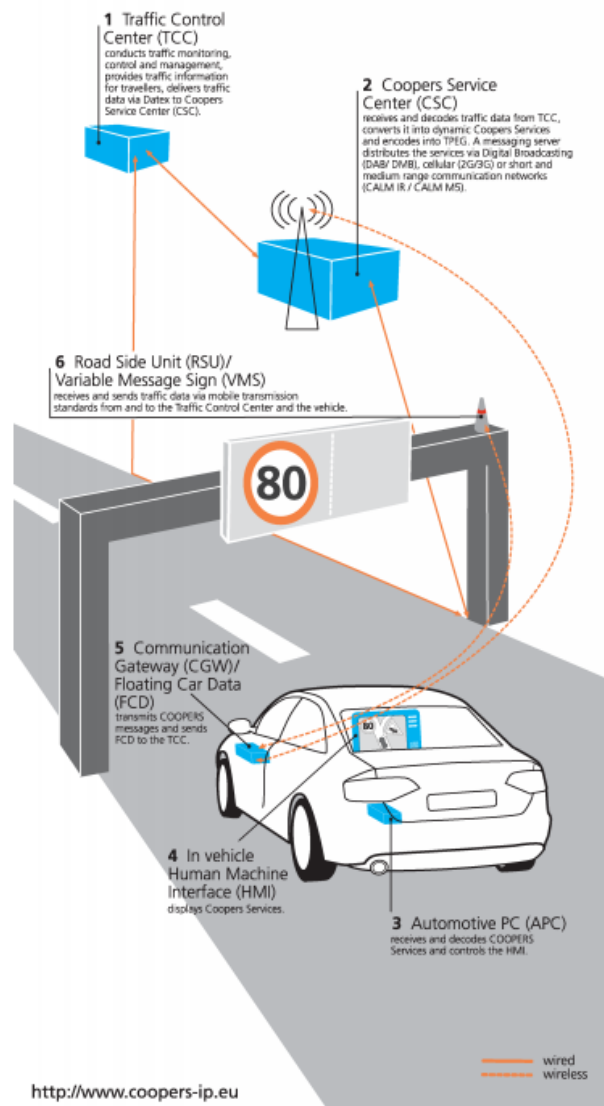


Fig. 4 - Elements of COOPERS system [9]

The system was tested in 2010 (January-June) on roads with heavy traffic in Western Europe (Fig. 5), these roads were equipped COOPERS systems. Tests were divided into several parts; in one part were conducted tests of only one entity of the system

- Test 1: Test took place on the roads in Germany, Austria and Italy, so there were also three different operators (Austria - ASFINAG, Italy - Autostrada del Brennero, Germany - OBB). Here was tested the increasing traffic safety through COOPERS and the concept of sending traffic information. Besides these two main goals, in this location researchers also tried handover between different operators and the acceptability of the system from the user perspective.

- Test 2: In this test they have focused not only on the efficiency of traffic management, but also on the effectiveness of control systems within the vehicle. Testing was conducted in the Netherlands and Belgium.
- Test 3: Researchers during this test were verifying the functionality of the system in an urban environment. The tests took place in Berlin.
- Test 4: In this test were tested COOPERS services, their effectiveness, impact on the safety and acceptability by the users. These tests were carried out in France.



Fig. 5 - Test locations of COOPERS project [9]

The tests were successful and showed an increase in safety and efficiency of traffic management but also the high acceptability of the system users. [9]

### 2.4.3. Ecomove

The project was realized between 2010 and 2013 and, like the previous project was co-financed from European Union funds. The project involved a lot of bodies from various disciplines (e.g. TomTom, Volvo, Continental, Bosch and BMW), who worked with a total budget of 22.5 million Euro (EU contributed with an amount of 13.7 million Euro). Ecomove, unlike most of the projects do not solve road safety, but his goal was to use C2X communication and "green" applications to reduce fuel consumption.

The project was divided into several subprojects (SP), which ran in order from the basic ones to most complex one and solves individual problems.

- SP1 - Planning and coordination between participants.
- SP2 - Research and development of key technologies that will form the "backbone system" and technical coordination between entities.
- SP3 - Developing applications for eco-driving car.
- SP4 - Developing applications for eco-driving for trucks and freight transport logistics
- SP5 – Development of applications for environmental management and management of traffic flow.
- SP6 - Testing and assessment of the impact of Ecomove services on driver behavior, traffic flow management efficiency and the environment and also analysis of costs and benefits of the deployment.

In the subproject 2, the research was focused on technologies, which will be necessary for system operation. These include:

- Vehicle to vehicle and vehicle to infrastructure communication platform, which was based on the results of previous studies.
- Reports, protocols and interfaces for the exchange of information between cooperating entities: floating car data that contains information about the position and fuel consumption of vehicles and are sent to other vehicles and to the Traffic Control Centre.
- A digital map, which is equipped with static and dynamic attributes such as road gradient, fuel consumption of other vehicles and vehicle speed on specific sections, traffic data and information about other vehicles.
- Cooperative horizon that gives drivers a preview of what the conditions prevail on the road before him. This information is collected from digital maps, Traffic Control Centre and other vehicles.
- Situational model containing behavior of the driver and dynamics of the surrounding traffic flow. This model is used to calculate the optimal transport strategies and predicts how the traffic situation changes depending on the behavior of drivers who are in the vicinity.

In the tests were included men and women aged 20 to 69 years. Most of them were professional drivers, but also the volunteers were tested. The results showed that by using this system we can reduce the amount of CO<sub>2</sub> generated by vehicles (passenger and freight vehicles), up to 25%. This system has proven greater potential on urban roads than non-

urban, mainly due to more frequent stops (road signs, traffic lights). Drivers equipped with the system drove more economically with fewer stops than the drivers, who were not equipped with the system, but to the goal destination they got a little slower, mainly due to slower acceleration and earlier shifting. The project did not show that the proposed system would have a negative impact on security, on the contrary, more drivers comply safe distance between vehicles and less exceeds of the speed limit. Acceptability of users was also at high level, users considered the system useful and efficient. Most of them would like to have a similar economic system in their cars. Still, most of the users would not pay for the system more, than the savings through the system.[10]

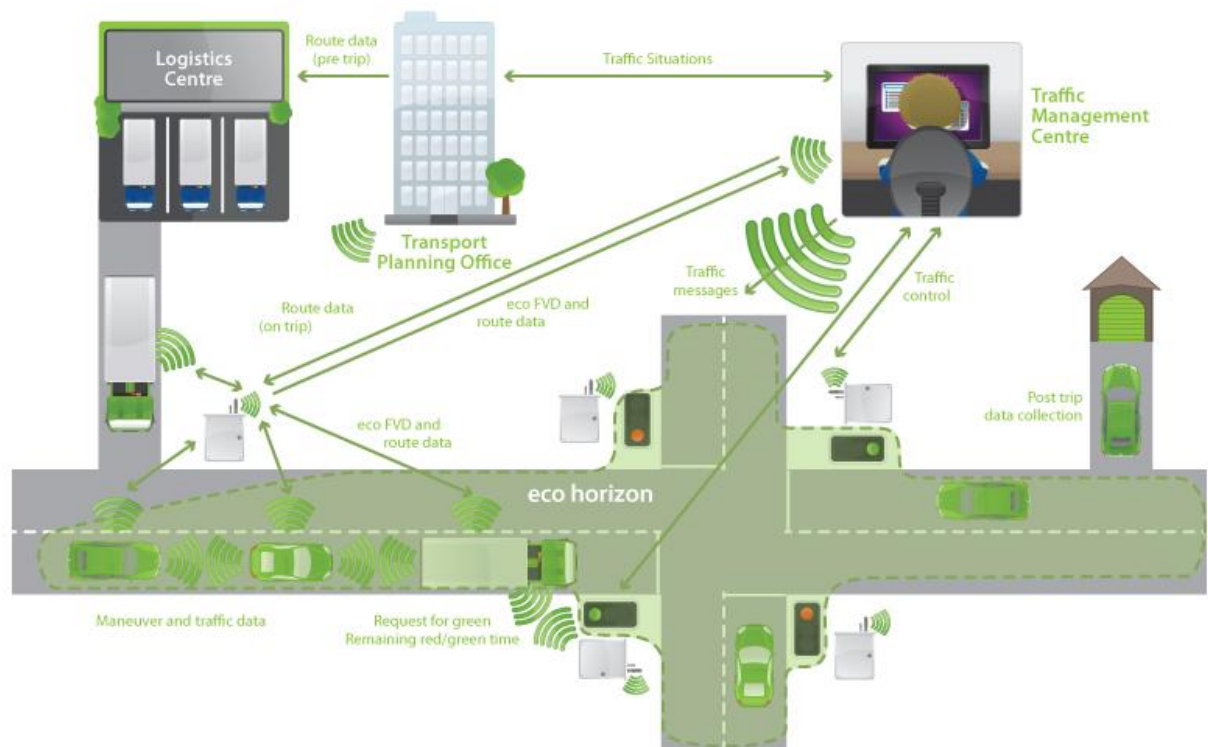


Fig. 6 - Architecture of Ecomove system [10]

#### 2.4.4. Drive C2X

The project began its work in January 2011 and lasted for 42 months to June 2014. It was created, like most of European projects, with the help of EU, particularly with the contribution of 12.4 million euros. So the total budget with all contributions was 18.6 million euro. Total of 34 institutions (e.g. Audi, BMW, Daimler, Ford, Volvo, Nokian) participated in this project. Drive C2X followed previous projects in this area (Cooper, PRE-Drive C2X, PReVENT or SAFESPOT). Goal of the project was development of cooperative system in Europe by spreading the awareness of these systems among the general public and provide feedback

to standardization bodies. They wanted to achieve this by several tests across Europe. (Fig. 7). [11]



Fig. 7 - test locations of project Drive C2X [11]

- Tampere, Finland  
Here, the tests were performed only on a small scale (4 participants) on public roads as well on roads, which are restricted to public (Nokian test track). Tampere was chosen because his arctic climatic conditions. It is ideal location to test applications associated with the weather.
- Gothenburg, Sweden  
In Gothenburg tests were performed on a larger number of participants (20 users). Like in Finland, tests were done on public and private roads (Volvo test track). Gothenburg is Sweden's second largest city, there is around 100 intersections equipped with traffic lights. On these roads were tested functions associated with transportation in the city (timing of traffic lights, warning before congestion, car breakdown warning)

- **Helmund, Netherlands**  
Testing area in the Netherlands includes several intersections equipped with traffic lights and the highway fully covered with 802.11p and CCTV. This was used during initial application testing before they were introduced to other six test locations.
- **Frankfurt, Germany**  
German testing site is located in Frankfurt, an important transport hub. This location is characterized by high traffic volumes, which allows to experiment with the safety and control functions in everyday conditions. In Frankfurt was performed the biggest test under Drive C2X with more than 100 test vehicles. Location was originally built for the project SimTD.
- **Yvelines, France**  
Test area in France was located in several places in Yvelines department, especially around Versailles. The area is being built under the French project SCORE@F. Initially the project was being built around the track Versailles - Satori, and then spread to adjacent areas. This area is ideal for testing of all kinds of scenarios, safety, efficiency and comfort.
- **Brenner, Italy**  
A test location is located in the north of Italy, near the town of Trento. Area for testing DRIVE C2X is 49 km long road section between the cities of Trento and Rovereto. All tests are carried out on public roads. The area offers full coverage GPRS / UMTS.
- **Vigo, Spain**  
Spanish test area is located in the northwest of Spain, in Vigo. It is about 60 km long area with speed roads and highways with entrances to the city. The area was created in the Spanish project SISCOGA. It is planned to extend the area also to an urban environment.

#### **2.4.5. Compass4D**

Project Compass4D started January 1, 2013 and officially ended 31 December 2015. However, the Compass4D consortium and its associated partners have decided to continue operating the C-ITS services, without EU co-funding, in the seven pilot sites for at least one year. Till December 2015 project's budget was 10 million Euro and involved 33 partners (e.g. Volvo, Siemens, SWARCO or Telecom Italia). The project focuses on three services that

enhance driver safety, driving comfort and reduce CO2 emissions and fuel consumption. These services are: red light warning, warning before dangerous situation on the road (obstacle, road works, and congestion) and energy efficiency intersection (trucks and public transport vehicles have the ability to set the green for them at intersection equipped with the traffic lights).

The goal of the project was to implement these three services in seven cities in Europe (Fig. 8). The researchers wanted: to show the positive effects of cooperative systems, to ensure the viability of applied systems and services, to become a reference model for other cities, to raise awareness about these systems and to promote international cooperation and standardization.[12]

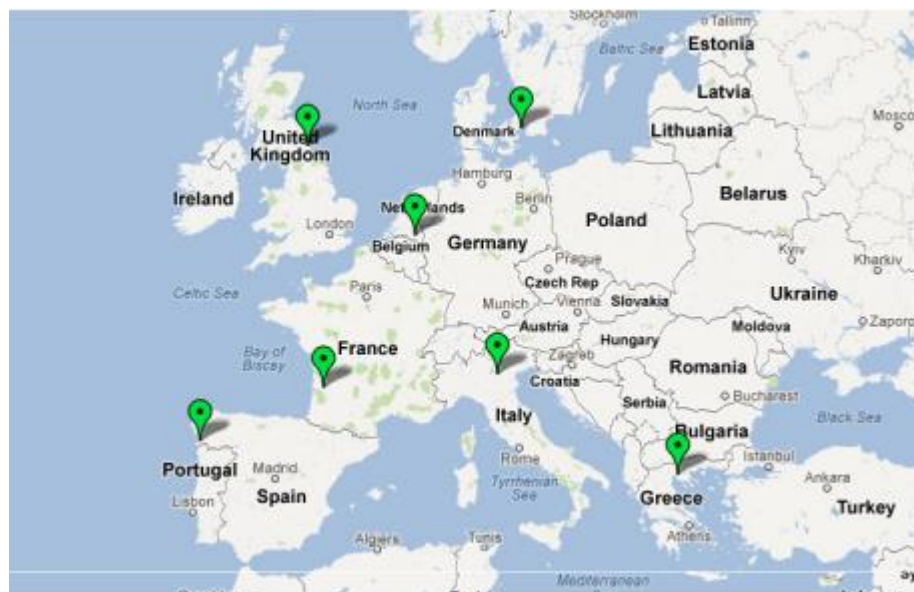


Fig. 8 - Test locations of project Compass4D [12]

These are the testing locations:

- **Bordeaux**  
French test locations is situated in Bordeaux, in the southwest of the country and includes urban and interurban roads. The area is managed and controlled by two traffic centers: Gertrude for urban and Alienor for interurban traffic management. Urban area is located in an area with heavy traffic, mainly due to the large business parks. An interurban area covers the city bypass. In total there was participating in tests 40 trucks, 34 passenger cars and 6 vehicles of the emergency services, totally 120 drivers. On the bypass was installed 7 communication nodes and 15 of these nodes was installed in the city.

- **Copenhagen**  
In Denmark was test site located in the center of Copenhagen. A road, chosen for the test, is one of the busiest bus routes, connecting two important stations. Ongoing construction of subway and a large number of different means of transport leads to the formation of congestions, which is a serious problem for public transport buses. For buses is the energy efficiency of intersections primary service and is implemented at 21 intersections. In test participated 86 buses, five trucks and two electric cars, totally 190 drivers.
- **Helmond**  
The Dutch trial locations are located in two cities Helmond and Eindhoven, and are part of DITCM (Dutch Integrated Test site for Cooperative Mobility). Here Compass 4D continued with the already implemented projects (e.g. Ecomove, CVIS, and DriveC2X). All three services was implemented in this location, with the intention to perform tests scenarios on both urban and non-urban roads. In tests participated 52 drivers in seven trucks, 25 electric vehicles, 5 buses and 5 vehicles of emergency services. 17 communication nodes were implemented in Helmond, 11 on the highway A270 and 7 in Eindhoven.
- **Newcastle**  
British test site is located in the east of the country, in Newcastle, while the area itself is located in the west of the city. The main road connecting the north and south of the city was equipped with 20 communication nodes. Road is surrounded by residential and commercial real estates. Two electric cars from Newcastle University and twelve ambulance cars were tested here.
- **Thessaloniki**  
Greek test site is in the region of Central Macedonia in Thessaloniki. In the city were chosen two test areas, one for each service. In Tsimiski Street, one of the main routes of the city (50,000 vehicles per day), was tested the energy efficiency service on the intersections. Warning before dangerous situation on the roads was tested on the ring around the city (100 000 vehicles per day), where are frequent accidents and thus formation of congestions. In each part were installed 7 communication nodes. Tests were attended by 35 vehicles, taxis and 7 cars.



- Verona

The tests also took place in northern Italy, in Verona. These tests were unique, because in these tests attended volunteers from the public. Together with these volunteers, 5 taxi cars and 5 cars borrowed from the city, in tests participated 40 cars and 10 buses. At strategic locations around the city have been deployed 25 communication nodes. In Verona was, for the first time in Europe, tested LTE in V2V and V2I communication.

- Vigo

The test area located in Spain is in the city of Vigo, in the northwest part of the country. The city has about 300,000 inhabitants. Because of tumultuous activities caused by a diversified economy passes the center of the city 480,000 vehicles per day, including a large number of trucks. Due to this fact and the boom of the city, traffic planning and management became big challenge. City continuously deploy infrastructure for monitoring and managing traffic flow in real time. In city were installed 17 communication nodes. In tests participated 10 passenger cars, 20 buses, 2 vehicles of emergency services and 8 vehicles of taxi. All of these vehicles drove 68 drivers.

#### **2.4.6. BaSIC**

BaSIC is one of the newer projects from the field of cooperative systems in Czech Republic. Project was funded under the program Beta of Technology agency of Czech Republic. The company INTENS Corporation Ltd. and the Czech Technical University - Faculty of Transportation Sciences began work on the project 28. 11. 2012 and ended it 31. 12. 2013.

The object of the project was analysis of status quo, pilot testing and implementation of cooperative systems in the Czech Republic and EU. The aim of the project was to design, develop and validate new comprehensive measures to increase road safety through cooperative systems, to propose technical and organizational conditions for the deployment of interoperable systems in the Czech Republic and to help overcome obstacles of the implementation of interoperable systems at the international level. Furthermore, they wanted to help the Czech Republic to create the conditions for safety critical applications using connection of vehicles with the transport infrastructure so that end users can rely on ITS application.

Within the project was also performed a pilot test of communication between vehicles and communication between vehicle and infrastructure. For the test was chosen the appropriate section on D0 (Prague ring) between Vestec and Jesenice (km 80 – 3.6) where is situated 6 portals of linear traffic management and 1 portal of variable message sign. Because of request from ŘSD, for the testing was selected only two applications, namely displaying current information from the variable message signs (positioned on portals) on display in the vehicle and warning about movement of vehicles of emergence services in the vicinity of vehicles. [13]

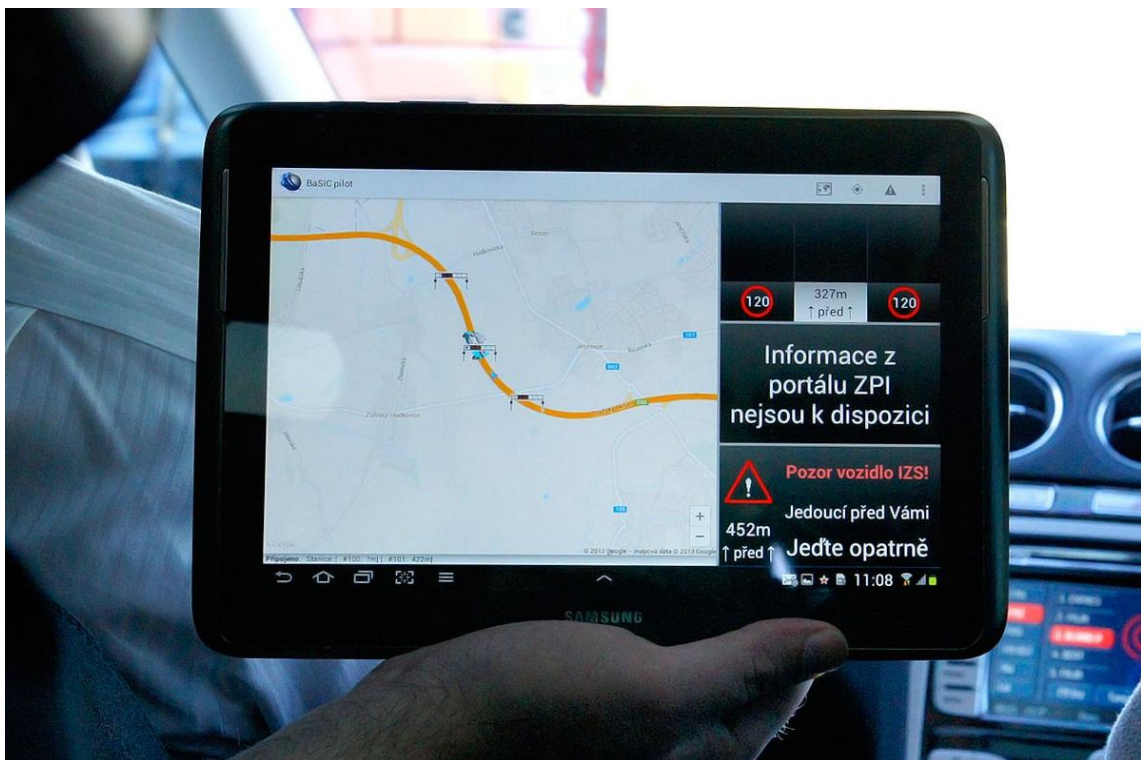


Fig. 9 - Testing of application about movement of emergency vehicles [15]

#### 2.4.7. TE-VOGS

Project TE-VOGS has been developed by Telematix services Inc. and Techniserv Ltd. in cooperation with the Czech Technical University - Faculty of Transportation sciences. TE-VOGS was built on the previous project CaMNA, which ran from 2004 to 2006. Both projects solved complex issue of monitoring and controlling the movement of the movable objects, around the airfield, using GNSS. Goal of the CaMNA was to verify, if is possible with the available technological means to create a telematics application, which would monitor the movement of vehicles on the airfield. It was created architecture of information and communication system, but due to lack of funds it was not implemented.

TE-VOGS is identification and communication system with navigation functions for airport vehicles, which serves primarily to the strength overall safety of airport. The system is designed for employees who operate the vehicles on the airfield, for supervisors and for air traffic control workers. The unit is equipped with the airfield map, which allows to an airport supervision and management staff to track vehicles (client stations) on the airfield. TE-VOGS allows monitoring, on the navigation screen inside the vehicle, of its own current position, current position of the other vehicles, and current position of maneuvering aircraft and also allows transfer of data between the vehicle and the dispatcher station, which improves the efficiency of air traffic controllers and significantly increases safety. [14] [16]



Fig. 10 - Example of the HMI of TE-VOGS [14]

#### 2.4.8. eCall

eCall is a project of European Commission, which task is to design, test and implement service, of the same name, to vehicles across the European Union. About this project talks since 2001, originally it should have been mandatory implemented in newly produced vehicles in 2009, due to the unreality of this term implementation was postponed to 2015, but was again postponed to 2017, which should be definitive term. eCall testing is carried out within the European project HeERO (Harmonised eCall European Pilot), which ended its activities 31. 12. 2013. In selected EU countries, including the Czech Republic, the test vehicles simulated traffic accidents for the purpose of authentication of error-free transmission of data and voice between the vehicle and the operators of 112 centers.

The project aims to help motorists involved in a traffic accident. eCall will be provided across the European Union. The system works on the basis of a single European emergency call 112. eCall consists of three main parts namely: OBU units, emergency call centers and telecommunications networks. OBU unit's task is to monitor the critical variables of the car and has two basic components, a GPS module that provides accurate information on the position of the vehicle at the time of activation and transmits this position to the second component, GSM module, which is designed to communicate with the emergency call centers. The system can be activated in two ways: manual and automatic. Manual mode will be activated by the driver in the creation of extraordinary events for example when the vehicle occupant started to have health problems or witnessing an accident in his vicinity. Automatic activation is triggered during a traffic accident. During these activation OBU unit connects to the nearest emergency call center, establishes a call between an operator in the center and the driver of the vehicle and sends the minimum data about the accident, called MSD. On the basis of this information, which will have an operator available in about 15 seconds, he has to decide about the extent of rescue operations and by this he can eliminate the serious health consequences of injured accident participants.

The system, however, has caused fear for privacy of drivers between certain groups of people, as it contains a GPS module, GSM module and a microphone. It is therefore theoretically possible that the system could be abused to track the location of a vehicle or wiretapping. However, the technical solution of the base system eliminates the use of eCall for any other purpose than to contact emergency services. The system is inactive until it is activated manually or automatically due to an accident. However, the system can be equipped by motorist assistance or surveillance (after theft) services, but only by free consent of the customer. According to the relevant legislation, preventing the operation of the system, or even its removal can be punished.[17]

Element	Description
ID	Version of MSD format
Message Identifier	eCall set identifier
Control	Type of activation, type of vehicle and reliability of vehicle position
VIN	Vehicle identification number
Propulsion storage Type	Type of fuel
Timestamp	Time of eCall event
Vehicle Location	Vehicle position – longitude and latitude
Vehicle Direction	Vehicle direction before the event

Recent vehicle location	optional; previous positions of vehicle
Number of passengers	optional; number of fasten seatbelts

Tab. 1 - Content of MSD

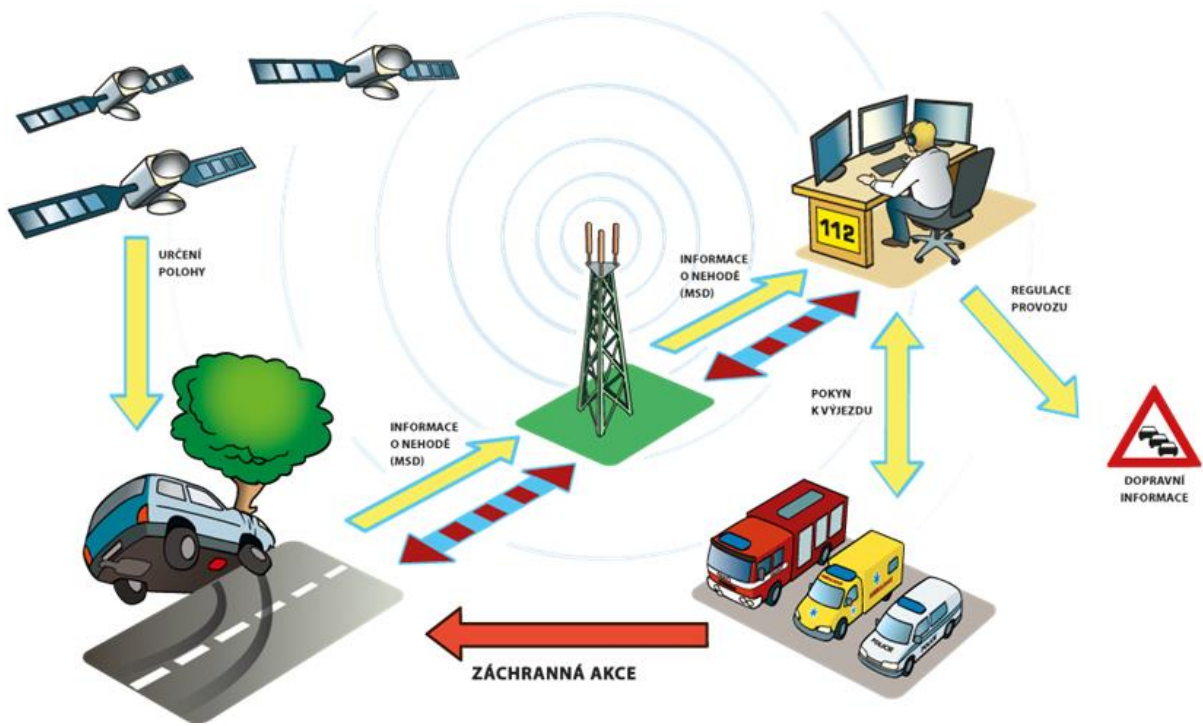


Fig. 11 - Scheme of eCall service [17]

### 3. Standards

Standard is a document, which specifies behavior, characteristics and requirements on different products, materials, systems and so on. Standards contain processes and methods, which ensure worldwide compatibility of products. Systems and products are compatible if they are produced according to related standards. From standards benefits both, users and producers. Users, because they are sure, if they buy some product, that it works in accordance with his other systems, if they are produced according the same standard (e.g. if user's mobile phone and car are equipped with Bluetooth - IEEE 802.15.1., he knows that these devices will communicate with each other). Producers benefit from lower costs for production of a system and higher acceptability of a product on the market. In this chapter I would like to describe three different standardization bodies, which play a major role in standardization process of cooperative systems. These organizations are: [20]

#### 3.1 ISO

ISO is an abbreviation for International Organization for Standardization. ISO is an independent and non-governmental organization consisting of 162 national standard bodies. These national standardization organizations delegate experts to international standardization committees (together there is 192 of committees) and these committees develop standards in all areas of standardization (from technology and agriculture to food safety). ISO was founded in 1947 and its headquarter is in Geneva. So far ISO produced more than 13 500 valid standards. ISO offers three types of membership for national organizations:[20]

- Full membership  
Full voting rights in any committee, one member for each country.
- Correspondent membership  
Full membership fees but no participation in development, only kept fully informed.
- Subscriber membership  
Reduced membership fees (for small economies), only informed about main standardization activities.

## **3.2 CEN**

CEN (European committee for standardization) was founded in 1961. Currently there are 33 members in the CEN. Most of them are members of European Union, for them are standards developed by CEN mandatory to accept. In some fields is CEN not developing their own standards, but they just adopt ISO standards. The official goal of the CEN is to enhance the economy of the EU in global trading, the welfare of European citizens and the environment by providing efficient infrastructure for the development, maintenance and distribution of standards and specifications. CEN is neither developing nor adopting standards from two fields, electro technical and telecommunications, for them are other European organizations: ETSI (telecommunications) and CENELEC (electro technic). [21]

## **3.3 ETSI**

ETSI (European Telecommunications Standard Institute), how I wrote above, is European organization responsible for standardization standards from telecommunication field. As the telecommunication standardization organization, ETSI publish the most important standards for cooperative systems and all ITS in Europe. ETSI was founded in 1988 and is based in Sophia Antipolis in France. In ETSI are currently more than 800 members from 64 states, similarly like ISO, there are more variants of membership. Full members are only EU member states, rest of them are associate members. ETSI produce about 2500 standards every year.[22]

## **3.4 C-ITS standards**

There are a huge number of standards from field of cooperative systems, it would be impossible to write about all of them, so I will write only about the most important ones. Most of these standards are still being developed, this only indicate, how tremendous development is in this area. For purpose of this work, I divided these standards into two categories:

- C-ITS Architecture standards
- C-ITS Testing standards

### 3.4.1 C-ITS Architecture standards

For purpose of this work, I divided Architecture standards according the OSI communication layers for cooperative systems

- Physical and data link layer
    - ETSI TS 102 687 v1.1.1 - Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range
- Decentralized Congestion Control Mechanisms (DCC) is a cross layer function, so this standard defines which DCC components are located on which layer of the ITS station communication architecture and specifies the DCC on the access layer. DCC shapes the network traffic to ensure proper operation of safety applications, so the DCC avoids access delay and packet collisions, which is important for safety critical systems. Functional view on DCC is provided on following Fig. 12.

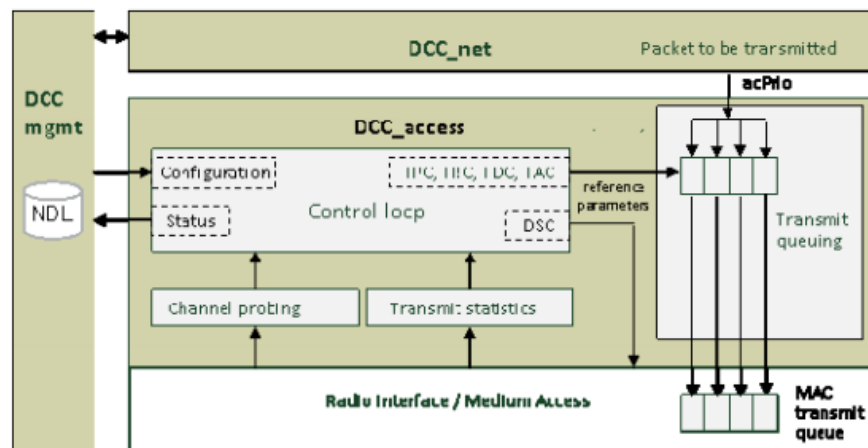


Fig. 12 - Functional view on Decentralized congestion control [23]

Standard also specifies all of DCC mechanisms, which are: transmit power control, transmit rate control, transmit datarate control, DCC sensitivity control, transmit access control, DCC transmit model and DCC receive model. [23]

- ETSI TS 102 724 v 1.1.1 - Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band
- In this document is presented the Channel-Configuration entity, the transmission to and reception from multiple channels. Channel-Configuration entity distributes traffic offered to the data link layer over a fixed set of channels available. It uses certain requirements under the control of the



corresponding DCC management entity. Example of multiple channels managed by Channel-Configuration entity is on following Figure

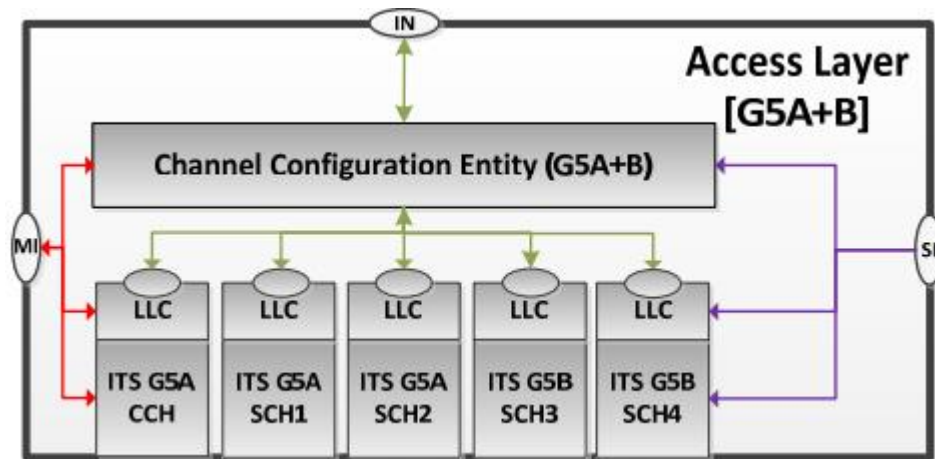


Fig. 13 - Managing of multiple channels by Channel configuration entity [24]

In the document are further specified requirements based on DCC profiles and congestion state. [24]

- ETSI ES 202 663 v1.1.0 - European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band

This standard specifies physical layer, medium access control sub-layer and their managing entities. The main requirement for both of the layers is that they have to be compliant with the 802.11 – orthogonal frequency division multiplex (OFDM). According to the standards, are for ITS reserved 3 frequency ranges:

- 5 905 MHz to 5 925 MHz – for future ITS applications
- 5 875 MHz to 5 905 MHz – for safety applications
- 5 855 MHz to 5 875 MHz – for non-safety applications

These ranges are further specified in EN 302 571, but the channel allocated in these ranges are described in this document. Regarding the Medium access control sub-layer, in this standard is described MAC frame, which consist of MAC header, frame body and frame check sequence.[25]

- IEEE 802.11 – Wi-Fi
 

IEEE 802.11 is a family of standards, used for physical layer and MAC specifications. The most important for ITS is IEEE 802.11p, which was described above, so I won't describe this standard more. These standards are still being developed; currently there is a plan for 802.11ax protocol to be released in 2019.[26]
- IEEE 802.3. – Ethernet
 

I chose to mention Ethernet, because it can be used for communication RSU with RSU or RSU with traffic center. Ethernet is a mainly LAN technology, but have some WAN applications. For connections are used copper cables, or in case of higher data rate are used optic fibers. Ethernet is being developed from 1980, so it is relatively old, but tested technology. The main characteristic of Ethernet is use of CSMA/CD protocol for access to transmission channel. CSMA/CD uses a a carrier sensing scheme, in which a trasmitting station detects collision with other signals while transmitting a frame, in that case station stops a transmission, then station send a jam signal and then waits for a random time, after that time it tries to send that data again.[27]
- ISO 11898-1:2015 - Road vehicles - Controller area network (CAN)
 

This standard defines the physical layer of CAN. This standard is mentioned here, because OBU has to communicate with the CAN bus to retrieve vehicle's parameters and characteristics. The CAN bus is a balanced (differential) 2-wire interface running over either a Shielded Twisted Pair (STP), Un-shielded Twisted Pair (UTP), or Ribbon cable. Each node uses a Male 9-pin D connector. The Bit Encoding used is: Non Return to Zero (NRZ) encoding (with bit-stuffing) for data communication on a differential two wire bus. The use of NRZ encoding ensures compact messages with a minimum number of transitions and high resilience to external disturbance. Start and stop bits control the beginning of each character in a asynchronous transfer, which is used by CAN bus.[28]
- Network and transport layer
  - ETSI EN 302 636-1/2/3 – Vehicular communications; GeoNetworking
 

This document is divided into 3 parts. First one is about requirements; second one about scenarios and the third one about network architecture for the GeoNetworking. GeoNetworking is a network-layer protocol for mobile ad hoc



composition is valid in case of unsecured packet, if we want to add security options (encryption, digital signature), we have to add to Payload GeoNetworking secured packet. There are also described protocol operations, which include network management and packet handling. Packet handling includes the procedures to determine geographical location, security functions and the functions that are specific for different packets (e.g. beacon packet or location service packet). [30]

- ETSI EN 302 636-5-1 v1.2.0 - Vehicular communications; GeoNetworking  
The fifth part is about Basic transport protocol (BTP). It is describing the same things like the previous standard, but for BTP, so we can find here the BTP packet structure (Fig. 15) and protocol operations.[31]

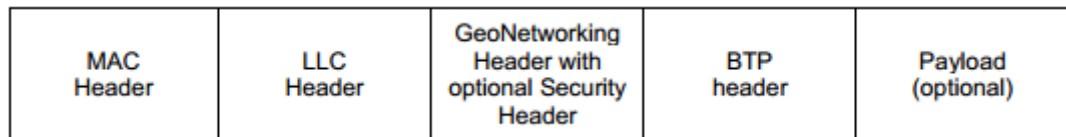


Fig. 15 - BTP packet structure [31]

- ETSI EN 302 931 v1.0.0 – Vehicular communications; Geographical Area Definition

Here is explained definition of geographical areas, which are used in vehicular communication. These areas are circular, rectangular and ellipsoidal (Fig. 16). We can also find here definitions of geometric function F, which is used to determine whether is a certain point located inside or outside of a geographical area. [32]

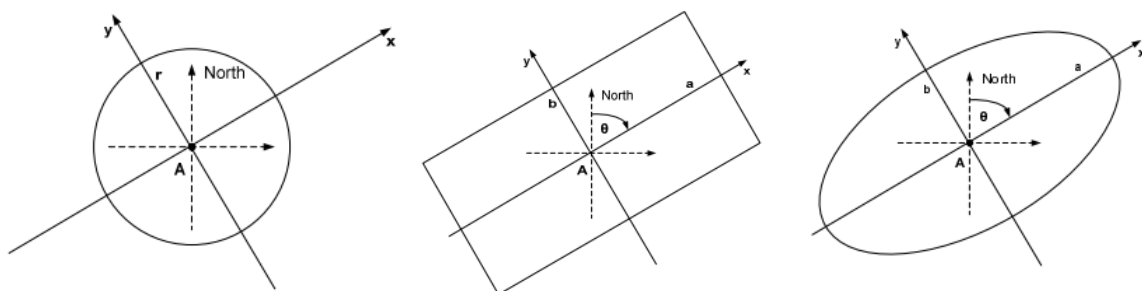


Fig. 16 - Geographical areas[32]

- Session layer

- ETSI EN 302 665 v1.1.1 – Communications architecture

How we can estimate from the name of the standard, this document specifies framework of communication in the road transportation. We can find here architectural elements of ITS communication and also parts of management and security entities in the ITS communication architecture. The ITS station reference architecture follows the principles of the OSI model for layered communication protocols which is extended for inclusion of ITS applications. The functional elements of ITS communication are following:

- personal ITS sub-system; in hand-held devices,
- central ITS sub-system; part of an ITS central system,
- vehicle ITS sub-system; in cars, trucks, etc.
- roadside ITS sub-system; on gantries, poles

The goal of the management unit is to manage networking, communication services, ITS applications and inter-unit communication. Similarly, goal of the security entity is to manage security functionality of the ITS communication, that means manage firewall, identity, crypto keys, certificates, authentication, authorization and so on.[33]

- Presentation layer
  - ETSI EN 102 894-1 v1.1.1 - Users and applications requirements  
This document specifies domain and common facilities (Tab. 2, Tab. 3) and functional requirements on them.

Classification	Identifier	Facility name	Short description
Management	CF001	Traffic class management	Manage assignment of traffic class value for the higher layer messages.
	CF002	ITS-S ID management	Manage ITS-S identifiers used by the application and the facilities layer.
	CF003	AID management	Manage the application ID used by the application and the facilities layer.
	CF004	Security access	Deal with the data exchanged between the application and facilities layer with the security entity.
Application support	CF005	HMI support	Support the data exchanges between the applications and HMI devices.
	CF006	Time service	Provide time information and time synchronization service within the ITS-S.
	CF007	Application/facilities status management	Manage and monitor the functioning of active applications and facilities within the ITS-S and the configuration.
	CF008	SAM processing	Support the service management of the management layer for the transmission and receiving of the service announcement message (SAM).
Information support	CF009	Station type/capabilities	Manage the ITS-S type and capabilities information.
	CF010	ITS-S positioning service	Calculate the real time ITS-S position and provides the information to the facilities and applications layers.
	CF011	Location referencing	Calculate the location referencing information and provide the location referencing data to the applications/facilities layer.
	CF012	Common data dictionary	Data dictionary for messages.
	CF013	Data presentation	Message encoding/decoding support.
Communication support	CF014	Addressing mode	Select addressing mode for messages transmission
	CF015	Congestion control	Facilities layer decentralized congestion control functionalities.

Tab. 2- List of common facilities [34]

Classification	Identifier	Facility name	Short description
Application support	DF001	DEN basic service	Support the protocol processing of the Decentralized Environmental Notification Message.
	DF002	CA basic service	Support the protocol processing of the Cooperative Awareness Message.
	DF003	EFCD	Aggregation of CAM/DENM data at the road side ITS-S and provide to the central ITS-S.
	DF004	Billing and payment	Provide service access to billing and payment service provider.
	DF005	SPAT basic service	Support the protocol processing of the Signal Phase and Timing Message.
	DF006	TOPO basic service	Support the protocol processing of the Road Topology Message.
	DF007	IVS basic service	Support the protocol processing of the In Vehicle Signage Message.
	DF008	Community service user management	Manage the user information of a service community.
Information support	DF009	Local dynamic map	Local Dynamic Map database and management of the database.
	DF010	RSU management and communication	Manage the RSUs from the central ITS-S and communication between the central ITS-S and road side ITS.
	DF011	Map service	Provide map matching functionality.
Communication support	DF012	Session support	Support session establishment, maintenance and closure.
	DF013	Web service support	High layer protocol for web connection, SOA application protocol support.
	DF014	Messaging support	Manage ITS services messages based on message priority and client services/use case requirements.
	DF015	E2E Geocasting	Deal with the disseminating of information to ITS vehicular and personal ITS stations based on their presence in a specified Geographical area.

Tab. 3 - List of domain facilities [34]

The example of that functional requirement on security access can be following:

This function exchanges with the security entity in order to receive security events notifications as required by the applications. It shall be able to receive the information from the security entity and provide them to the applications or the facilities requesting such information.[34]

- ETSI EN 302 637-2 v1.3.1 – Vehicular communications; Basic set of applications; Specification of cooperative awareness basic service

Standard gives overview about cooperative awareness messages (CAM) and content of this message. CAM is message exchanged in the ITS network between ITS stations to create and maintain awareness of each other and to support cooperative performance of vehicles using the road network. This message basically says: I am vehicle in this position and these are my parameters. Between mandatory parameters belongs for example: position, heading, speed, width and length of the vehicle, curvature and so on. We can say that the CAM message contains all the relevant information about the vehicle. This message is broadcasted to everyone in the vicinity of the vehicle.[35]

- ETSI EN 302 637-3 v1.2.1 – Vehicular communications; Basic set of applications; Specification of decentralized environmental notification basic service

Decentralized environmental notification messages (DENM) are the second type of messages, which are exchanged between ITS stations. DENM is triggered by unexpected event and then the ITS stations start to broadcast this messages. DENM contains information related to a road hazard or an abnormal traffic conditions, such as its type and its position. The information from the DENM is send to the driver if information of the road hazard or traffic condition is assessed to be relevant to the driver. The driver is then able to take appropriate actions to react to the situation accordingly. Between mandatory data belongs only detection time, reference time, position of the event and station type, so it is not even mandatory to specify type of the event.[36]

- ETSI EN 102 894-2 – v1.2.1 - Users and applications requirements; Applications and facilities layer common data dictionary

This document works as a dictionary that includes list of data elements and data frames that represent data as well as information necessary for the realization of ITS messages (e.g. CAM and DENM). In dictionary is described in detail what is content of the data elements and data frames, what are the units used by the data frame element, what is the expected size of the data frame and element and so on.[37]

- ETSI TS 102 637-1 v1.1.1 – Vehicular communications; Basic set of applications; functional requirements and ETSI TS 102 638-1 v1.1.1 – Vehicular communications; Basic set of applications; definitions

The basic set of applications (BSA) is list of defined applications, which can be deployed within three years after the complete standardization of the system. This is the difference between BSA and the “day one applications”, because day one applications are considered to be deployed right after the complete standardization. Complete list of BSA is in Tab. 4.

Applications class	Application	#(see note)	Use case
Active road safety	Driving assistance - Co-operative Awareness (CA)	UC001	Emergency vehicle warning
		UC002	Slow vehicle indication
		UC003	Intersection collision warning
		UC004	Motorcycle approaching indication
	Driving assistance - Road Hazard Warning (RHW)	UC005	Emergency electronic brake lights
		UC006	Wrong way driving warning
		UC007	Stationary vehicle - accident
		UC008	Stationary vehicle - vehicle problem
		UC009	Traffic condition warning
		UC010	Signal violation warning
		UC011	Roadwork warning
		UC012	Collision risk warning
		UC013	Decentralized floating car data - Hazardous location
		UC014	Decentralized floating car data - Precipitations
		UC015	Decentralized floating car data - Road adhesion
		UC016	Decentralized floating car data - Visibility
		UC017	Decentralized floating car data - Wind
Applications class	Application	#(see note)	Use case
Co-operative traffic efficiency	Speed Management (CSM)	UC018	Regulatory/contextual speed limits notification
		UC019	Traffic light optimal speed advisory
	Co-operative Navigation (CoNa)	UC020	Traffic information and recommended itinerary
		UC021	Enhanced route guidance and navigation
		UC022	Limited access warning and detour notification
Co-operative local services	Location Based Services (LBS)	UC023	In-vehicle signage
		UC024	Point of Interest notification
		UC025	Automatic access control and parking management
		UC026	ITS local electronic commerce
Global internet services	Communities sServices (ComS)	UC027	Media downloading
		UC028	Insurance and financial services
		UC029	Fleet management
	ITS station Life Cycle Management (LCM)	UC030	Loading zone management
		UC031	Vehicle software/data provisioning and update
		UC032	Vehicle and RSU data calibration

NOTE: The identifier of the use case is defined and used only within the present document.

Tab. 4 - Basic set of applications [38]



In the document are also specified communication scenarios between vehicle and vehicle and between vehicle and ITS station (RSU). All the scenarios are very similar, they are only different in the source and the receiver of the data and by impulse, which is triggering start of the communication. In the last part of the standard are specified functional requirements on all of the applications from the basic set. Example of the requirement is on the Fig. 17.

**[FR\_UC001\_009\_VS]** | If DENM is sent, the application at the originating vehicle ITS station shall define the transmission latency requirement and the priority of the "emergency vehicle warning" DENM.

Fig. 17 - Example of functional requirement for BSA [38]

- ETSI EN 302 895 v1.1.1 – Vehicular communications; Basic set of applications; Local dynamic map

Local dynamic map (LDM) is a database of objects influencing or influenced by road traffic. ITS applications need for their proper operation information about moving (vehicles) and stationary objects in their vicinity (road signs, traffic lights). Storage of this information is maintained by LDM. LDM receive data from the various sources e.g. other vehicles, sensors on the board, traffic center or RSU stations. LDM allows to applications to access the data stored in the database according their authentication.

In the standard are also specified interfaces between LDM data consumers and LDM data providers in different situations like data request, authorization or delete message. In the standard, interfaces are defined as information flows.[39]

- Application layer

- ETSI TS 101 539-1 v1.1.1 – V2X applications; Road hazard signaling application requirements specification

Standard describes road hazard signaling application (RHS), which is entity in the ITS station and triggers transmission of messages (e.g. CAM or DENM). RHS also process incoming messages from other ITS stations. Goal of the RHS is to provide information about road hazards ahead of the driver. Use cases of RHS are following (can be extended in the future):

- 1) Emergency vehicle approaching
- 2) Slow vehicle
- 3) Stationary vehicle

- 4) Emergency electronic brake lights
- 5) Wrong way driving
- 6) Adverse weather condition
- 7) Hazardous location
- 8) Traffic condition
- 9) Roadwork
- 10) Human presence on the road

There are also stated functional requirements for these use cases and for the application operation.[40]

### **3.4.2 C-ITS testing standards**

- ETSI EG 202 798 v1.1.1. – Testing; Framework for conformance and interoperability testing

Conformance testing is a testing that implemented system is compliant according to protocol standard. If it is compliant or is not compliant is decided by the test, which runs test script against the implementation. Interoperability testing tests, if the device can interoperate, according to the standards, with the devices from different vendors. In the document are described test methods and test scenarios of these tests. Conformance and operability testing will be more described in the next chapter.[41]

- ETSI TS 102 868-1/2/3 V1.1.1 – Testing; Conformance test specification for cooperative awareness message; Part 1; Part 2 and Part 3  
In the first part of this set of standards, about testing of CAM, are defined instructions for completing the forms and forms for testing data elements and data frames of CAM.

In the second part is specified test suite structure with its groups and subgroups and similarly like in the first part, we can find here instructions and forms for testing of TSS groups and subgroups. Groups are following:

- Message generation
- ITS profile checking
- Information adaptation
- Position adaptation
- Message processing

Group information adaptation is further divided into subgroups. Examples of these subgroups are: Siren in use, Exterior lights, Dangerous goods, Occupancy and so on. The last part of the document is defined abstract test method, how to understand the results of abstract test suite and the forms for the abstract tests. Scheme of the abstract protocol tester is on Fig. 18.

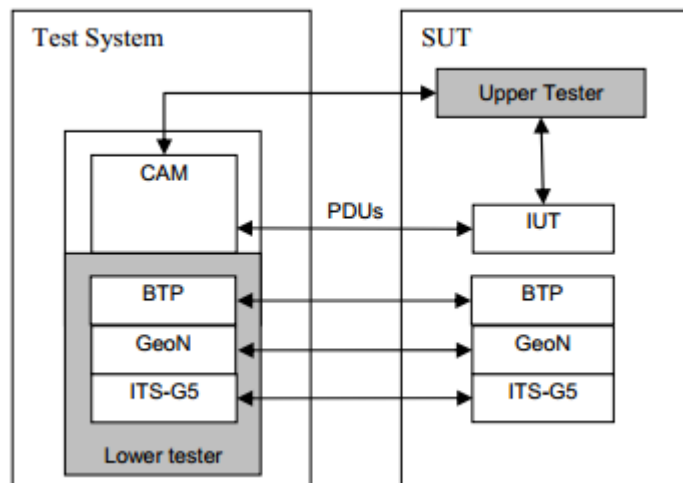


Fig. 18 - Abstract protocol tester [42]

Test system simulates valid and invalid behavior of the protocol and then the test system will analyze the response of tested implementation.[42]

- ETSI TS 102 869-1/2/3 V1.4.1– Testing; Conformance test specification for Decentralized Environmental Notification Messages; Part 1; Part 2 and Part 3 Similarly like in the case of testing CAM, in the first part of this set of standards, about testing of DENM, are defined instructions for completing the forms and forms for testing data elements and data frames of DENM.

In the second part is specified test suite structure with its groups (in case of DENM there are no subgroups) and similarly like in the first part, we can find here instructions and forms for testing of TSS groups and subgroups. Groups are following:

- Message format
- Event generation
- Event update
- Event termination
- Message repetition

- Lower-layer parameters
- Message reception
- Keep-alive forwarding

The last part of the document is defined abstract test method, how to understand the results of abstract test suite and the forms for the abstract tests. Abstract tester looks the same like in the case of testing the CAM messages.

Test system simulates valid and invalid behavior of the protocol and then the test system will analyze the response of tested implementation [43]

- ETSI TS 102 870-1/2/3 V1.1.1– Testing; Conformance test specification for GeoNetworking basic transport protocol (BTP); Part 1; Part 2 and Part 3

Similarly like in the case of testing CAM or DENM, in the first part of this set of standards, about testing of GeoNetworking, are defined instructions for completing the forms and forms for testing data elements and data frames of GeoNetworking BTP.

In the second part is specified test suite structure with its groups (in case of GeoNetworking BTP there are no subgroups) and similarly like in the first part, we can find here instructions and forms for testing of TSS groups and subgroups. Groups are following:

- Packet generation BTP-A
- Packet generation BTB-B
- Packet processing

The last part of the document is defined abstract test method, how to understand the results of abstract test suite and the forms for the abstract tests. Abstract tester looks the same like in the case of testing the CAM messages.

Test system simulates valid and invalid behavior of the protocol and then the test system will analyze the response of tested implementation. [44]

ETSI TS 102 871-1/2/3 V1.1.1– Testing; Conformance test specification for GeoNetworking ITS-G5; Part 1; Part 2 and Part 3

Similarly like in the case of testing CAM or DENM, in the first part of this set of standards, about testing of GeoNetworking ITS-G5, are defined instructions

for completing the forms, test configurations and forms for testing data elements and data frames of GeoNetworking ITS-G5.

In the second part is specified test suite structure with its groups and subgroups and similarly like in the first part, we can find here instructions and forms for testing of TSS groups and subgroups. Groups are following:

- Formatting and data validity
- Protocol operation
- Buffer capacities
- Media dependent tests

In the last part of the document is defined abstract test method, how to understand the results of abstract test suite and the forms for the abstract tests. Abstract tester looks the same like in the case of testing the CAM messages. Test system simulates valid and invalid behavior of the protocol and then the test system will analyze the response of tested implementation.  
[45]

## **4. Verification of cooperative systems**

We have to verify cooperative systems from more than one perspective, because cooperative systems are complex systems with non-trivial functions. If we want to use C2X systems, we must ensure that the systems met the requirements regarding quality of transmission of information, safety of transmitted information, compliance with standards or interoperability between the parts of the C2X systems. For this purposes was created conformance and interoperability testing, which is described in the standard ETSI EG 202 798, which is mentioned above, but we want to focus on them in this chapter. We want to also mention telecommunication and telematics performance parameters, which we have to monitor during design and implementation phase in order to achieve properly operating system according our expectations.

### **4.1 Conformance**

As we stated above, conformance testing is a process during which we decide if processes, which are happening in the system are according to the standards. In this chapter we will focus only on conformance testing methodologies in the ITS. Object for testing is called is called Implementation Under Test (IUT) and usually it is just some part of the system, which we want to test. The system, in which is IUT implemented, is called System Under Test (SUT). In order to properly test the SUT it has to be connected through at least one interface with the test system. Interface connecting SUT and test system is called Reference Point. IUTs are the same for both conformance and interoperability testing. IUTs, which we can test in the area of ITS are in the following table.[41]

Layer/entity	IUT (protocols)	ITS specific	Notes
Apps	ITS-S application messages	YES	Not considered for conformance testing. To be used for interoperability testing.
FL	CAM [i.18]	YES	
	DENM [i.18]	YES	
	Legacy CI port manager [i.16]	YES	
	15628 kernel emulator [i.16]	YES	
NL	Basic transport protocol for GeoNetworking [i.17]	YES	
	FAST networking and transport protocol [i.16]	YES	
	GeoNetworking [i.17]	YES	
	IPv6 for ITS [i.9]	YES	No test of IPv6 functionality from IETF, but only tests on how to use this functionality in the context of ITS.
	IPv6 over GeoNetworking [i.17]	YES	
	ITS-MUX [i.16]	YES	
	Legacy protocols such as TCP, UDP	NO	
AL	CAL extension for legacy systems [i.16]	YES	
	CALM IR [i.11]	YES	
	CALM M5 (ITS-G5) [i.12]	YES	The basic MAC and PHY is standardized in IEEE 802.11 [i.38] and thus not subject of tests within this ITS framework.
	CALM medium service access points/support of legacy technologies [i.14]	YES	
	Legacy technologies	NO	Covered by other testing frameworks.
ME	FAST service advertisement [i.15]	YES	
	Legacy system support [i.15]	YES	
SE	To be defined	YES	Base standards are under development.

Tab. 5 - Tested IUTs in ITS

On Fig. 18 in chapter 5.4.2 was showed Abstract protocol tester. Abstract protocol tester provides a situation of communication which is equivalent to real operation between real ITS devices. Test system simulates valid and invalid behavior of the protocol and then the test system will analyze the response of tested implementation.

Test system with the IUT exchange messages, which are called Protocol Data Units (PDUs). These messages start the process in the IUT and analyze the reactions from the IUT. The verdict, if it is according to standards or not, is based on the comparison of these reactions from the IUT and the expected reactions, which are explained in the related standards. In case of conformance testing we can also distinguish parts of System Under Test (SUT) into following components:

- Implementation under test (IUT)
- Upper tester application – simulates sending and receiving data from/to management or security layer
- ITS lower layers – connects SUT via physical link
- Upper tester transport – enables communication of upper tester application with the test system

In sense of ITS is conformance testing more related to software and telecommunications than hardware. Fortunately in ITS field are standards very precise and made with high quality. In some other areas is possible that the standards are not published properly or may be that the standards itself are of poor quality.[42]

## 4.2 Interoperability

Interoperability testing checks if the devices can inter-operate between themselves. Tests for interoperability are realized by connecting devices from different vendors and operating them (manually or automatically, depends on the device). These devices have to inter-operate according to scenarios, which are published in related standards.

In conformance testing we called the tested objects Implementation under test (IUT), in Interoperability testing we call the tested subjects Equipment Under Test (EUT). An EUT is a physical implementation of an ITS station or a physical implementation of a functional subset of an ITS station, which interacts with one or several other EUTs via one or more RPs. Typical example of interoperability testing could be exchange of CAM messages between vehicles from different manufacturers and RSUs. EUTs in this example would be OBUs stationed in the vehicles and roadside units. In case of ITS is strongly recommended that the SUT should be composed of at least 3 vehicles and 2 RSUs in order to completely cover all possible scenarios.[19][41] [49]

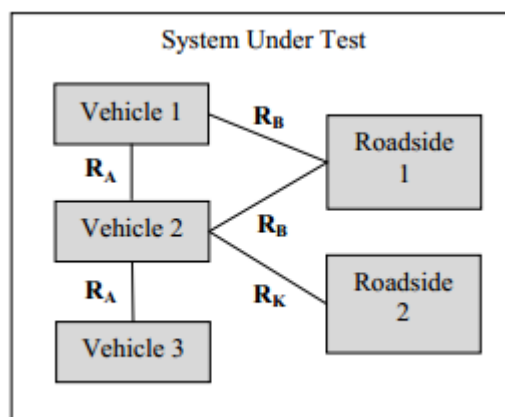


Fig. 19- Recommended SUT

We should consider the following when we are designing tests:

- All scenarios and use cases should be covered
- The design should support online and offline interoperability test execution as well the automatic and manual execution
- It should work for stationary vehicles and moving vehicles.
- Test should provide interfaces for:
  - Configuring the EUT
  - Stimulating the EUT
  - Monitoring the EUT
  - Tracing the execution of tests



During testing we classify the interfaces to three groups:

- Data: In this group belongs interface where data is exchanged. Depending on the type of data we can recognize three subgroups:
  - Stimulating: These interfaces are used to exchange the data, which is used to stimulate the EUT
  - Monitoring: Monitoring interface contains data, which are exchanged between UTs during operation of SUT
  - Tracing: Here we can find the data containing information about the status of execution of EUT.
- Control: Control group is used to configure and control the EUTs
- Test operator: This group provides the capability to select the test to be executed and to analyze results

Interoperability testing is more related to HW than SW, unlike the conformance testing. Vendors are interested, if their implementations can inter-operate with implementations from other vendors, before any test scripts for conformance testing are ready. Implementation conforming to a standard doesn't mean that it is inter-operable and inter-operable standard also doesn't mean that it is conforming to a standard.[41]

### **4.3 Performance indicators**

Conformance and inter-operability testing are methods, which are used during and after implementation to certificate that ITS are working properly. Before designing we have to define so called performance indicators, which are used for defining the parameters of the system according to requirements. These parameters are important for choose of individual components of the system and overall solution. We can use them to quantify a qualify processes. Processes have to fulfill set of parameters, which mathematically express the quality of the system. After chose of performance indicators we have to ensure that all devices and subsystems fulfill them. Before we will introduce performance indicators we would like to introduce the RSSI, which doesn't belong between performance indicators, but it is important in telecommunications. [16]

## Received signal strength indication

RSSI is a term used in telecommunications. It is a measurement of the power present in a received signal. RSSI is an indication of the power level being received by the antenna. Therefore, the higher the RSSI number, the stronger the signal. RSSI is usually visible to the user, because lower RSSI can negatively affect the functionality in wireless networking. RSSI is calculated: [14][16]

$$RSSI [dBm] = RSCP [dBm] - \frac{Ec}{Io} [Db]$$

RSCP (received signal code power) is total received energy after noise filtering and other corrections

$E_c/I_o$  is ratio of received energy and energy of received noise.

### 4.3.1. Telematics performance indicators

In this kind of indicators we define system parameters of processes in the telematics system. Further are the definitions of these telematics parameters according to [16]

- **Accuracy**

Accuracy is defined as the level of correspondence between measured and the defined value of parameter/processes/function:

$$P(|p_i - p_{m,i}| \leq \varepsilon_1) \geq \gamma_1$$

I.e. difference between required parameter  $p_i$  and measured parameter  $p_{m,i}$  doesn't exceed value  $\varepsilon_1$  at the level of probability  $\gamma_1$ . Defined formula is valid even on the vectors of parameters.

Requirement on the telematics application is that the error of accuracy in the position information will not be higher than 5m at the level of probability 99 %, what means that during the test the error of accuracy will not be higher than 5 m in the 99 % of cases.

- **Reliability**

Reliability is the ability of the system to fulfill required functions/processes without interrupting during the procedure in the defined time interval:

$$P(|\vec{v}_t - \vec{v}_{m,t}| \leq \varepsilon_2) \geq \gamma_2, t \in \langle 0, T \rangle$$

I.e. difference between required parameters (vectors of parameters)  $\vec{v}_t$  and measured parameters  $\vec{v}_{m,t}$  doesn't exceed value  $\varepsilon_2$  at the level of probability  $\gamma_2$  during arbitrary time  $t$  of time interval  $\langle 0, T \rangle$ .

In case of information about position we understand reliability as a division of availability of the position service regarding to total time  $T$  of observing this information. For example is required 99 % reliability at the level of probability 99 % in one hour, this means that in 99 tries from 100 tries in one hour is service in operation i.e. service is not available 36 s from one hour.

- **Availability**

Availability is the ability of the system to fulfill required functions/processes during the initialization of the system/process according to procedure:

$$P(|q_{m,i} - q_i| \leq \varepsilon_3) \geq \gamma_3$$

I.e. difference between a required value of successful initialization of function/process  $q_i$  and measured value  $q_{m,i}$  doesn't exceed value  $\varepsilon_3$  at the level of probability  $\gamma_3$ .

In the case of telematics application can be defined maximum time of initialization (time from activation of application to time of availability of application). In case of GPS localization is this time 30 s at the level of probability 99 %. This means that in case of 100 random initialization of localization service, only in one case is the initialization of the service longer than 30 s.

- **Continuity**

Continuity is the ability of the system to fulfill required functions/processes without interruption (maximum allowed time of interruption is defined) during the procedure (or defined time interval):

$$P(|r_t - r_{m,t}| \leq \varepsilon_4) \geq \gamma_4, t \in \langle 0, T \rangle$$

I.e. difference between required maximal interruption  $r_t$  and measured value  $r_{m,t}$  doesn't exceed in every time  $t$  in interval  $\langle 0, T \rangle$  value  $\varepsilon_4$  at the level of probability  $\gamma_4$ . Continuity is similar to reliability; difference is in observing the length of interruption. In the case of reliability we can observe one long interruption or a lot of small interruptions; continuity can differentiate between these two cases and define, how long interruption is allowed.

For example the requirement can be the maximal length of the interruption can't exceeds 5 s in the interval of 5 mins at the level of probability 99 %. I.e. from 100 tries only one time happens that in the 5 min interval is interruption longer than 5 s.

- **Integrity**

Integrity is the ability of the system to inform (in right time and precisely) the user, that system is not able to execute the functions/processes in the procedure

$$P(|s_i - s_{m,i}| \leq \varepsilon_5) \geq \gamma_5$$

I.e. difference between required time for reporting the fault  $s_i$  and the measured value of time for reporting the fault  $s_{m,i}$  doesn't exceed value  $\varepsilon_5$  at the level of probability  $\gamma_5$

Integrity states the ability of the system to diagnose exceeding of predefined parameters and inform the user about it in the required time interval.

- **Safety**

Safety is the ability of the system to prevent damages on the system, material loses or human injuries in the case of fault. Quantification comes from analysis and qualification of risks:

$$P(|W_i - W_{m,i}| \leq \varepsilon_6) \geq \gamma_6$$

I.e. difference between required risk situation  $W_i$  and real risk situation  $W_{m,i}$  doesn't exceed value  $\varepsilon_6$  at the level of probability  $\gamma_6$ .

Safety as a system parameter divides errors/faults, which are developing to the safe direction, these are malfunctions, which are characterized by reliability, continuity,

integrity and so on and errors/faults which are developing to the dangerous direction. Finding out safe and dangerous states is part of the qualification and analysis of risks.

#### 4.3.2. Telecommunications performance indicators

Telecommunications performance indicators are system parameters of the telecommunications system. Further are the definitions of these telecommunications parameters according to [16]

- **Activation time of available service**

Activation time of available service is defined as a time needed for activation of system from the functionless state to fully function state.

$$P(|a_i - a_{m,i}| \leq \varepsilon_1) \geq \gamma_1$$

I.e. difference between required time of successful activation of the system  $a_i$  and measured time activation time  $a_{m,i}$  doesn't exceed value  $\varepsilon_1$  at the level of probability  $\gamma_1$

- **Availability of service**

Availability of service is the ability of the system to fulfill required functions without interruption during the defined time interval:

$$P(|ca_t - ca_{m,t}| \leq \varepsilon_2) \geq \gamma_2, t \in \langle 0, T \rangle$$

I.e. difference between required parameters  $ca_t$  and measured parameters  $ca_{m,t}$  doesn't exceed value  $\varepsilon_2$  at the level of probability  $\gamma_2$  in every time  $t$  in the interval  $\langle 0, T \rangle$

We can say that the availability of the service is time of the unavailable service divided by time when service is available. In telecommunications is availability of the service often in the interval of one year

- **Mean time between failures (MTBF)**

MTBF is defined as a time between two unexpected faults at the at some probability level.

$$P(|f_i - f_{m,i}| \leq \varepsilon_3) \geq \gamma_3$$

I.e. difference between required mean time between failure  $f_i$  and real value of this parameter  $f_{m,i}$ , which is less than  $\varepsilon_3$  at the level of probability  $\gamma_3$ .

If is MTBF at the level of probability much bigger than reliability time interval  $\langle 0, T \rangle$ , we can consider this parameter as irrelevant

- **Mean time to restore (MTTR)**

MTTR is defined as a time needed for restoring the service from the fault state at some level of probability.

$$P(|rc_i - rc_{m,i}| \leq \varepsilon_4) \geq \gamma_4$$

I.e. difference between required value  $rc_i$  and real value  $rc_{m,i}$  of restoration time after the fault has to be less than  $\varepsilon_4$  at the level of probability  $\gamma_4$ .

- **Latency**

Latency is defined as a time delay of packet delivery between source and target destination during defined time interval at some level of probability

$$P(|d_t - d_{m,t}| \leq \varepsilon_5) \geq \gamma_5, t \in \langle 0, T \rangle$$

I.e. difference between required value  $d_t$  and measured value  $d_{m,t}$  doesn't exceed value  $\varepsilon_5$  at the level of probability  $\gamma_5$

Latency can be affected by:

- Transmission rate
- Size of packet
- Load of each node through which the connection passes

- **Packet loss**

Packet loss is defined as a percentage of non-delivered packets from the total amount of sent packets within the predefined time at some probability level:

$$P(|pl_{t,d}/pl_t| \leq \varepsilon_7) \geq \gamma_7, t \in \langle 0, T \rangle$$

I.e. number of delivered packets  $pl_{t,d}$  divided by total number of sent packets  $pl_t$  is equal or bigger than  $\varepsilon_7$  at the level of probability  $\gamma_7$  for every time  $t$  from interval  $\langle 0, T \rangle$

- **Safety**

Safety is the ability of system to prevent damages in telecommunication system in the case of fault:

$$P(|Wc_i - Wc_{m,i}| \leq \varepsilon_6) \geq \gamma_6$$

I.e. difference between required value of risk situation  $Wc_i$  and real value of risk situation  $Wc_{m,i}$  doesn't exceed vale  $\varepsilon_6$  at the level of probability  $\gamma_6$ .

## 5. Methodology

In this chapter will be introduced complete methodology for proper testing of parameters of cooperative systems designed within the project Opponent's review of cooperative systems in CZE pilot project. We will try to clearly comment the test procedure and specify the set of verification parameters. Please take into consideration that this is complete methodology. Performing this complete methodology is very costly in terms of time and equipment, thus it is correct to jump over some steps assuming that the cooperative system passed the next test. If cooperative systems don't pass the test, we have to go back and perform the jumped over test. We will not mention tests that are in competence of V2X systems manufacturers (e.g. RF output power or power spectral density) because they are more connected to the hardware of units of V2X systems than the implementation, so in this case we have to trust the manufacturers, that they followed all the standards during the designing and producing the unit.

First is tested the lowest communication layer, physical layer, then we are moving up through the communication layers up to application layer. With this approach we can discard the failure of the lower layer if we find out failure in the layer we are testing.

### 5.1. Physical layer tests

Tests of physical layer are the first step in verifying correct function of V2X systems. Physical layer is defined in standard ETSI ES 202-663, but only for systems used in European Union. Countries, which are not in EU, can have slightly modified parameters and structure of communication layers. In standards is communication technology defined as ITS G5 (older name is DSRC 5.9) .It is important to start with the tests of physical layer, because once we tested it, we can exclude failures of this layer in case of failures in upper layers. To be sure that physical layer of ITS devices is working correctly the tests should be following:

- Frequency allocation

By this test we determine whether the V2X communication unit is transmitting signal on the frequency defined by standard and also by this test we determine whether the device is transmitting something, because it can be malfunctioning and not transmitting at all. Frequency band reserved for ITS purposes is 5 855 MHz to 5 905 MHz for both, safety and non-safety applications. So the ITS device has to work in this band and be able to tune up to any of the five 10 MHz channels in the band, which correspond to IEEE channels 172-180.



- Channel bandwidth  
Channel bandwidth should be 10 MHz according to standard.
- Transmission channel  
Communication units should be tested whether they can communicate on the same channel without any errors and with 100 % of packets delivered (0 % packet loss).
- Dual receiver  
Standard requires that communication units should listen to two channels while not transmitting. These channels are G5 control channel and G5 service channel. This test is especially demanding, as we need setup of three devices. One of them transmitting on the service channel, second one transmitting on the control channel and third device has to listen on both channels.
- Bit rate  
V2X devices don't communicate only at one constant bit rate. ITS G5 uses different bit rates at service and control channel. The default bit rate of communication devices is 6 Mbps for control channel and 12 Mbps for the service channels. But it can be changed by using different modulation schemes. For this purpose is the communication bit rate defined in the header of physical layer, the header itself is always coded in 3 Mbps. Bit rate is chosen by the transmitter, possible bit rates are 3,4,5,9,18,24 and 27 Mbps.
- Transmission range  
Communication range depends on lot of factors which are difficult to quantify. Between those factors belong line of sight (LOS) and non-line of sight (NLOS) conditions, transmitter and receiver movement, surfaces that cause multipath propagation and obstacles that cause shadowing and diffraction. Object of this test is to determine range on which given communication devices can reliably communicate. This is the only test of physical layer which should be carried outside. The test should be carried out under controlled and reproducible conditions with two vehicles equipped with V2X systems according the manufacturer's manual. During the test, vehicles should increase space between them to the point, when they lose the communication. The minimum range is not standardized by ETSI, but the C2C-Communication consortium agreed, that the minimum communication range in LOS conditions should be 300 m.

- RSSI

The last test of physical layer is measuring RSSI of communication units. It is appropriate to measure RSSI not only in time, but with combination of GPS tracker so we can derive RSSI in dependency of range or actual position.

In most of the V2X communication units we can change communication parameters in some command line application or graphical configuration application. The first four tests should be carried indoor in an appropriate range in order to reduce influence of receiver sensitivity or output power. The only test which should be done outdoor is test of transmission range. To perform the tests we need two V2X communication units (three for the dual receiver test). First one should generate the traffic and the second one has to log the traffic, then we can see and calculate the results.[24][25][26][46]

## 5.2. Data link layer tests

Goal of the data link layer is to direct the communication by control mechanisms and addressing. Data link layer is also responsible for providing Quality of Service by these mechanisms. In ITS G5, like in 802.11p, is used CSMA/CA approach (in other 802.11 standards is used CSMA/CD). Data link layer should add data link layer header to the given packet, which contains data like source and destination MAC address, BSSOD, QoS etc. The tests are from major part consisting of examining of this data link header. Tests for testing of data link layer should be following: [25][47]

- QoS

QoS in V2X systems is provided by EDCA (Enhanced Distribution Channel Access) mechanism. There are four Access Categories (AC) in which is the traffic distributed and according these categories, priority is allocated to the packets. To perform this test we need three V2X stations, one should act like a receiver and two stations should transmit the packets with different priority to the receiver. The cooperative system passes the test if the packet loss of the packets with the higher priority is lower than the packet loss of packets with lower priority.

- Source MAC address

As some hardware MAC addresses are programmable it is possible that two neighboring V2X stations have the same MAC address. Because of it the V2X stations should monitor if stations in their vicinity have different MAC addresses and in case of conflict generate new MAC address.

- Destination MAC address

V2X stations should support broadcast and unicast communication, this is done by filling up the destination address field in the data link header. In case of broadcast communication all the bits in the destination address should be set to one.

### 5.3. Network and transport layer tests

Next are tests of layers above the data link layer, these layers are network and transport layer. Networking and transporting of packets in V2X system is done by GeoNetworking protocol. Standards of GeoNetworking were described above, I only want to remind, that there are three routing schemes: GeoUnicast, GeoBroadcast and Topological broadcast. GeoBroadcast delivers packets to a given destination area (circular, rectangular or ellipsoidal) with as many hops as GeoBroadcast needs to serve all units in the area. It is mostly used for transmission of DENM, because we can precisely define the area on the road and it makes sense only for the cars in this area to be informed about some event (e.g. car accident). GeoUnicast is just point to point communication, if one vehicle wants to inform only one other vehicle about some facts. E.g. it can be used in cooperative adaptive cruise control, when the leading car is informing the car behind about his acceleration. Topological broadcast broadcasts packets to all vehicles, which are in the range defined in the packet header. This range is in hops, so we can define that this packet will be transmitted to vehicles, which are in range of 5 hops. This function is used mostly in CAM. [29][30][31][32][47]

In order to check, if network and transport layers are working properly, we have to test all three routing schemes, unfortunately we need in most of these tests at least three V2X communications units. The tests are following:

- GeoBroadcast

This test checks the ability of V2X communication units to broadcast packets only to destination area. In this test are needed three communications units. First one is acting like sender and therefore is broadcasting packets to the defined area. Second unit is placed in this area and third unit is placed outside of defined area. Then we simply checks, if packets were transmitted only to the unit inside the area.

- GeoUnicast

This test checks the ability of V2X communication units to transmit packets directly between two communication units. For this test we only need two communication units. First one is sender and the second is receiver. We only place them in the range of each other and start to send packets from the receiver. After this, we just check if the packets were delivered to the receiver.

- Topological broadcast

This test checks the ability of V2X communication units to broadcast packets in the defined number of hops. To perform this test is needed at least three communication units. The first one is acting like sender. It will send packets with defined number of hops, in case of three communication units is the number of hops two. Then we will place second communication units in the range of the first unit. The third unit will be placed in the range of the second unit but outside the range of the first unit. After the test, packets have to be delivered to the third communication unit and the number of hops in these packets needs to be zero.

- Store and forward ability

In this test we check if the ability to store and forward stored data is performed correctly. We need to store packets in case, when there are no communication units in the range, so if we broadcast these messages, nobody would receive it. For storing is used buffer, which is part of the networking layer. When the V2X unit detects that there is a unit in the range, the stored packets are forwarded to it. For this test we need 2 communication units. The first unit is sender and the second unit is receiver. Sender generates GeoBroadcast or Topological broadcast packet, while the receiver is out of range. Then we will move to the range of the sender and check if the packet was broadcasted at the time, when the receiver was entering range of the sender.

## **5.4. Session, presentation and application layer testing**

Top three layers are tested together. We are not testing directly these layers, but it is more appropriate and efficient to test the execution of one or more applications from the Basic set of applications. So in these test we will observe transmissions of CAM messages and DENM messages (their completeness and correctness) between more participants and other behavior of V2X systems, like informing and warning the user.

It is possible to test function of V2X systems just on one application, but more appropriate is to choose combination of them. The most suitable applications for testing are:

- Emergency vehicle warning
- Roadworks warning
- Wrong way driving
- Overtaking vehicle warning
- Intersection collision warning
- Traffic light optimal speed advisory
- Electronic toll collections
- SOS service
- Fleet management

As you can see, represented are applications with the different behavior, like collision warnings and electronic toll collection on the other hand. So the tests for testing these applications are following: [34][35][36][37][38][47]

- CAM and DENM messages generation  
First we have to check if CAM messages are generated periodically and then broadcasted in the correct and complete form. Then we can check DENM messages. We have to test that these messages are generated according to events in the surroundings of vehicle. Events are detected by a large number of sensors, e.g. accelerometer, activation of ESP or status of brakes. If DENM messages are generated we have to ensure ourselves that they are transmitted to other vehicles.
- Relevance tests  
In this test we have to check if the delivered DENM message is relevant for the driver. When deciding if the message is relevant to the driver we have to take into consideration information like direction of vehicle, speed of vehicle, position of vehicle, distance to the event or type of the vehicle.
- Displaying and revoking of the warnings  
During these test we will check whether the most relevant warning at the present time was displayed to the driver through HMI. Of course on the other hand we have to check if the expired warning was replaced by the new one, when it was not relevant anymore.

- Delay

In the last test we have to measure delay between messages (DENM or CAM) creation and the moment of displaying the warning derived from the received message. There are no maximal limits of delay given by the standard because it strongly depends on the application. We should to keep delay as small as possible, around 100 ms is ideal value.

## 6. Testing in a real world

Methodology introduced in the previous chapter was used within the project Implementation of cooperative systems in the environment of Czech highways. Unfortunately, methodology has to be modified due to numerous reasons. Between the reasons belongs:

- Lack of communication units (with only two communication units we were unable to test some functionalities)
- Limited given time for our testing purposes
- Not fully controlled and reproducible conditions
- We didn't have access directly to the communication units or their parameter settings, so some tests were not possible to perform

So in our modified methodology we had to remove some test due to reasons mentioned above but the functionality of the methodology was preserved but in case of complications it would be much less efficient to find an error. In this chapter I would like to describe our modified methodology, present main results and also present the circumstances of our testing.

Roadwork warning is the only application which was tested, because it was the only application which was implemented within this project. Goal of this application is to inform road users about location of the roadworks, geometry of lanes, speed limit or presence of the workers. Application increase the overall safety on the section of the road, where are roadworks present.

### 6.1. Testing location

Tests were performed on two locations. First of them was complex of highway maintenance center Svojkovice (Fig. 20) at 57<sup>th</sup> km of D5 highway.



Fig. 20 - Highway maintenance center Svojkovice [48]

Second testing site was the D5 highway itself. Test was performed between 50<sup>th</sup> and 57<sup>th</sup> km of D5 (Fig. 21) during the regular traffic.

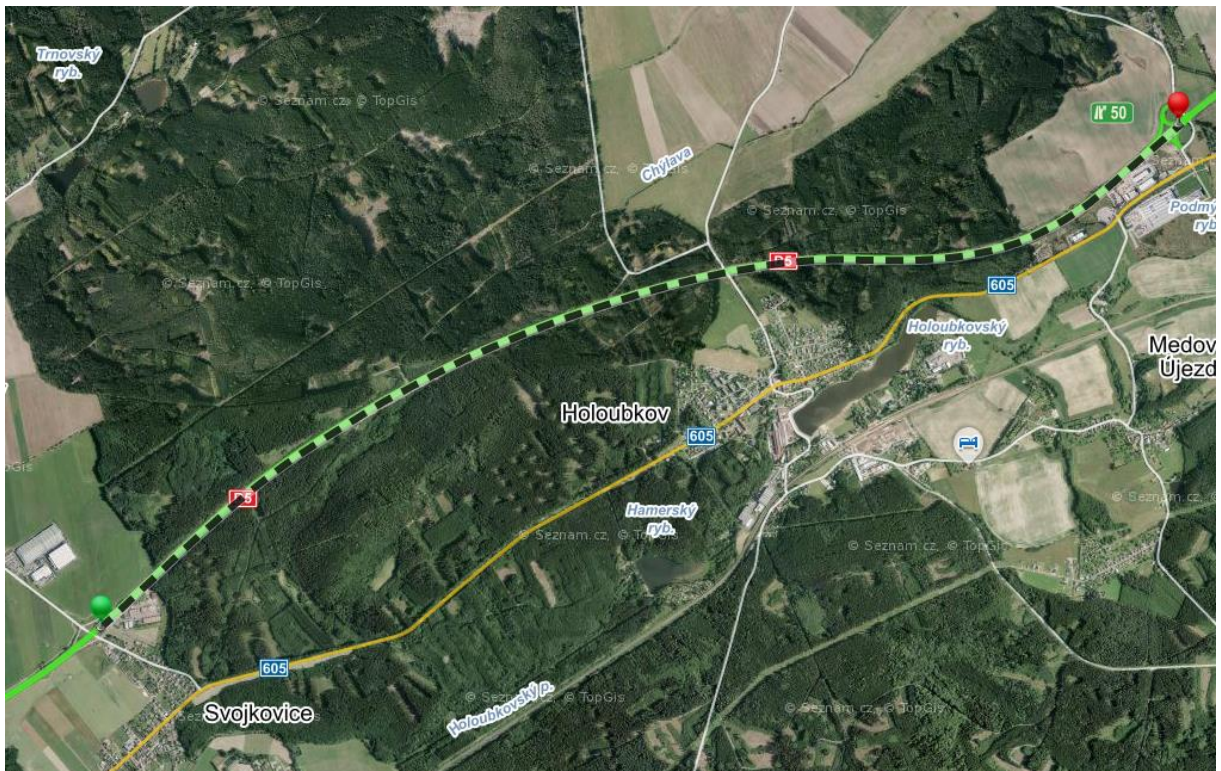


Fig. 21 - 50<sup>th</sup> and 57<sup>th</sup> km of D5 highway [48]



## 6.2. Testing equipment

During the tests and for processing results were used following equipment and programs:

- Wireshark program version 1.12.6 with ITS plugins
- Two OBU units Kapsch EVK-3300
- Two RSU units Kapsch MTX-9450
- Four DSRC antennas 1.7-6GHz MGRMWHF-3C-BLK-120
- Router Mikrotik
- Two tablets Samsung Galaxy TAB 4 10.1 served as HMI
- Spectrometer for measuring frequency spectrum and SW from spectrometer
- Two GPS units
- Two vehicles – Toyota (with unit named EVK61) and Lexus (with unit named EVK74)



Fig. 22 – Spectrometer during testing

## 6.3. Tests

In this chapter is described modified methodology (divided by layers, like in the full methodology) and performed tests. Description of main findings will be done in the next chapter.

### 6.3.1. Physical layer

As we stated above, first we have to test the frequency allocation of the signal transmitted by V2X communication units. This is done by spectrometer, which measures RSSI on different frequencies. On figure (Fig. 23) we can see that there are some signals in the reserved frequency with RSSI -85 to -90 dBm.

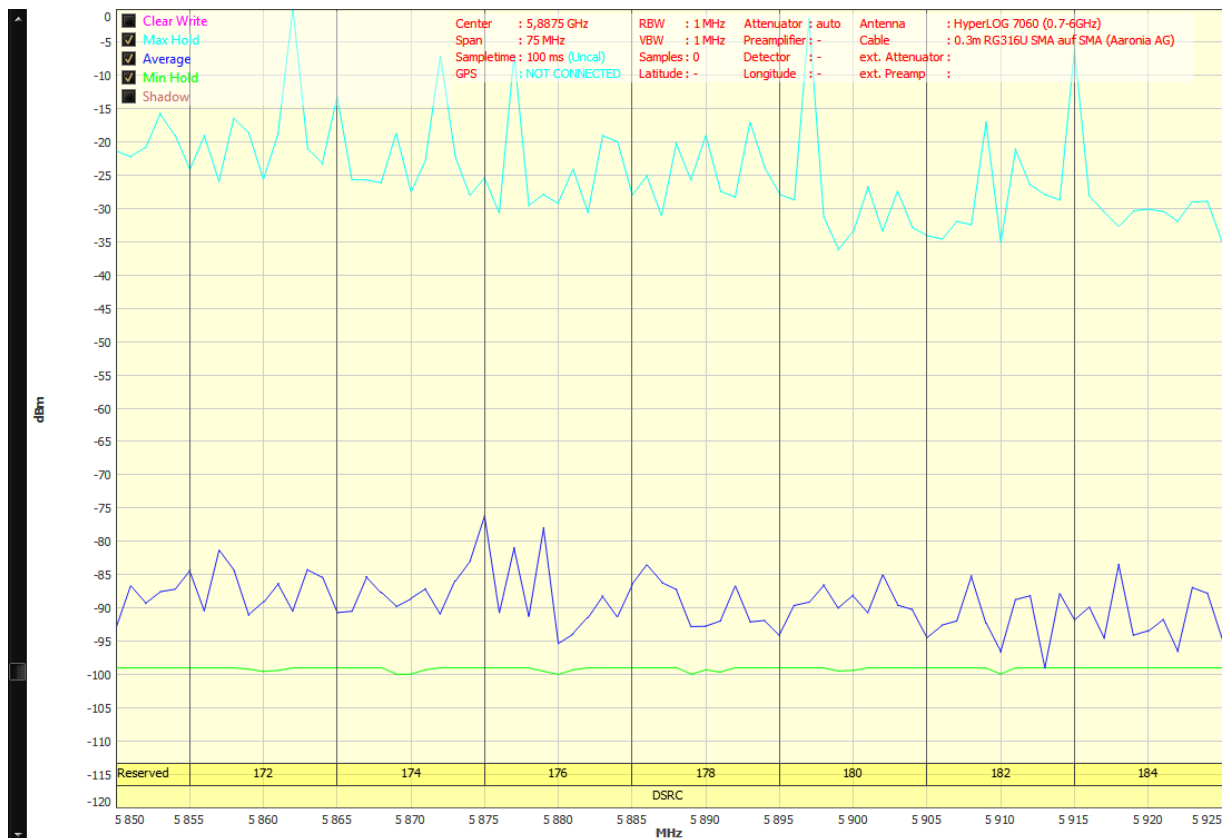
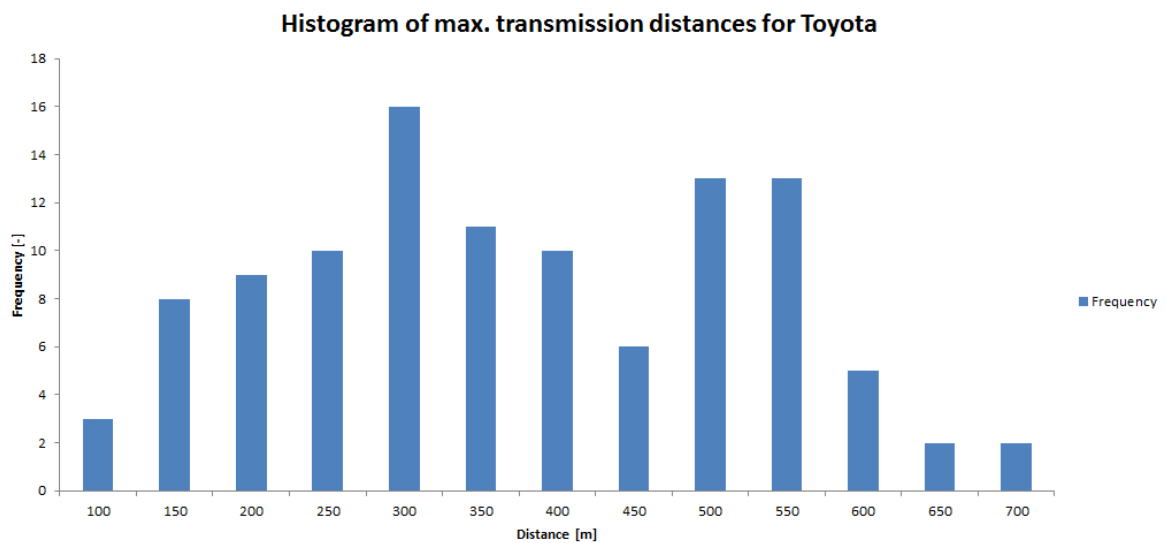


Fig. 23 - Frequency allocation testing

Next test of physical layer which we performed is test of transmission range. For this purpose were vehicles equipped with GPS units that were continuously saving their position, so we know where is the vehicle located in the exact time. For checking maximum transmission range we have to send packets from one vehicle to another vehicle and vice versa. It is

important to increase distance between the vehicles till the moment, when the packets stops transmitting. Then from GPS units we were able to calculate the exact maximum transmission distance between the vehicles. This test was performed on the highway during usual traffic. On the graph (Graph 1) we can see histogram of maximum transmission distances for Toyota vehicle, so it is distance, when Toyota stopped to receiving packets from Lexus. We can see that in the most of the cases were distances higher than recommended 300 m. In 30 cases from 109 were maximum transmissions distances lower than 300 m. On the picture (Fig. 24) we can see that most of the transmission distances lower than 300 m were measured on the curves surrounded by forests, where were not guaranteed LOS conditions.



Graph 1 - Histogram of max. transmission distances for Toyota

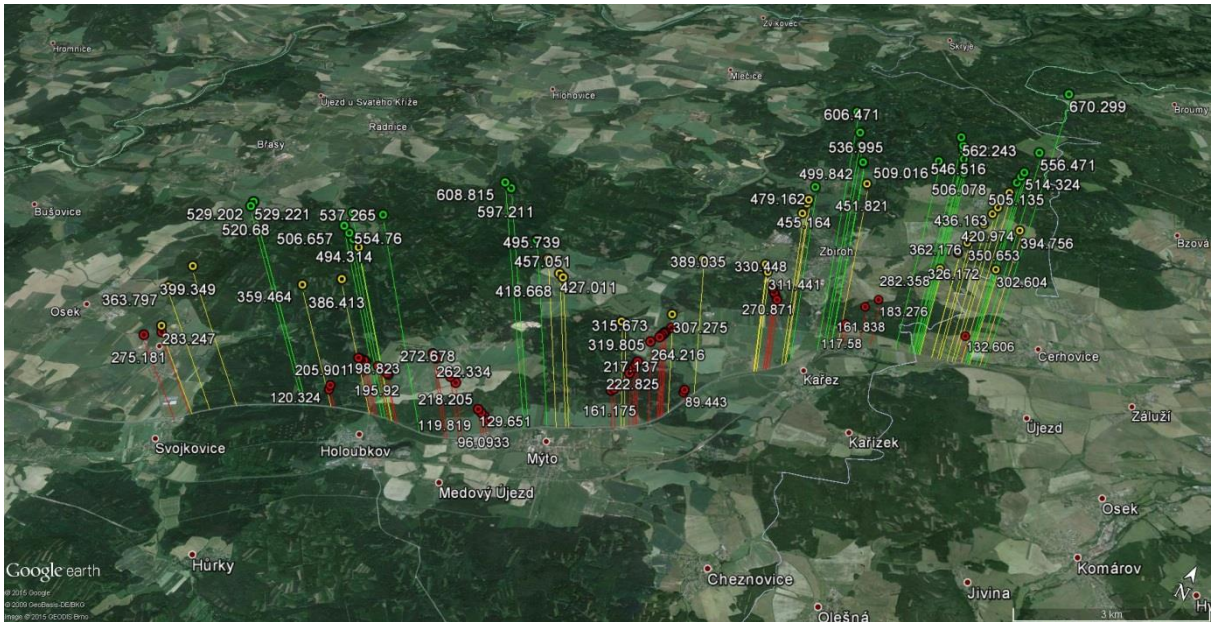
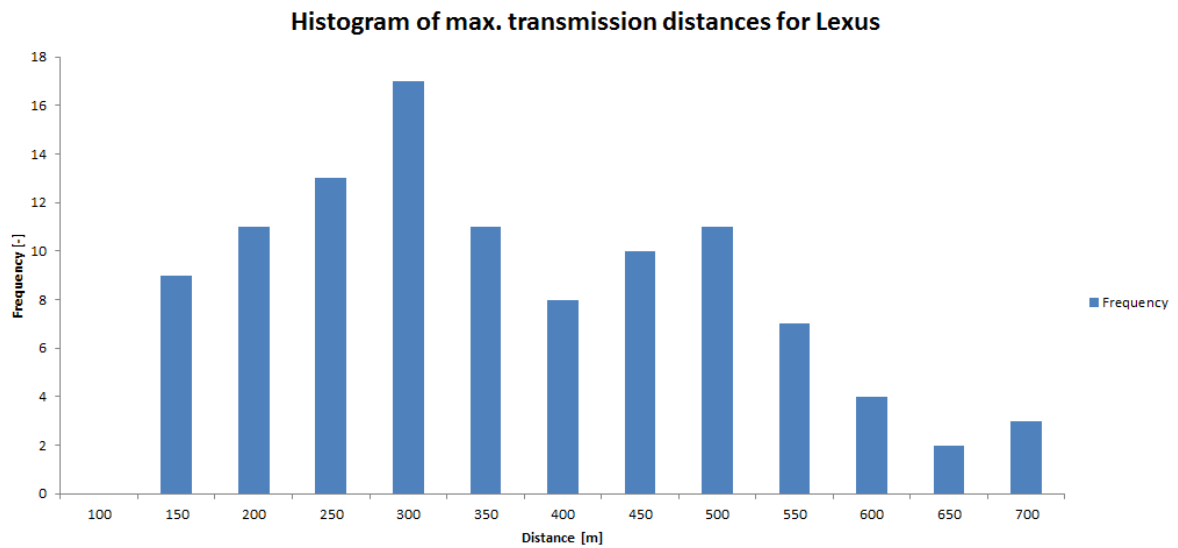


Fig. 24 - Max. transmission distance in the map for Toyota

On the next graph (Graph 2) and picture (Fig. 25) is similar information, only for the second vehicle, which was Lexus. The values are very similar, transmission range lower than 300 m were measured only in non-LOS conditions (curve, forest, above horizon).



Graph 2 - Histogram of max. transmission distances for Lexus

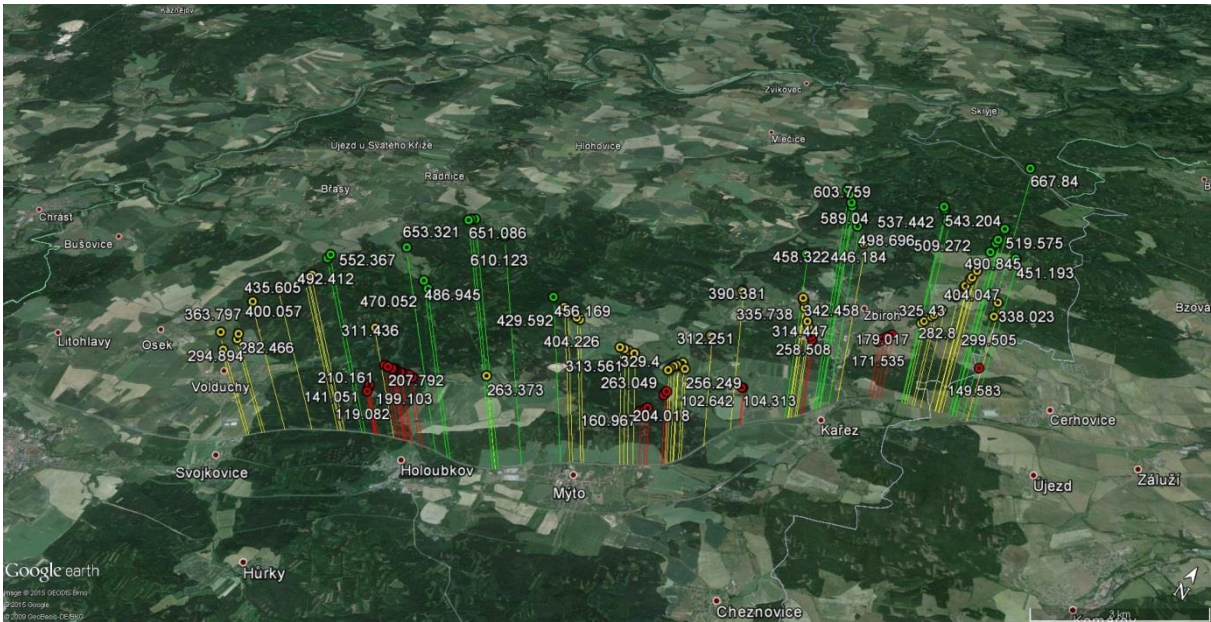
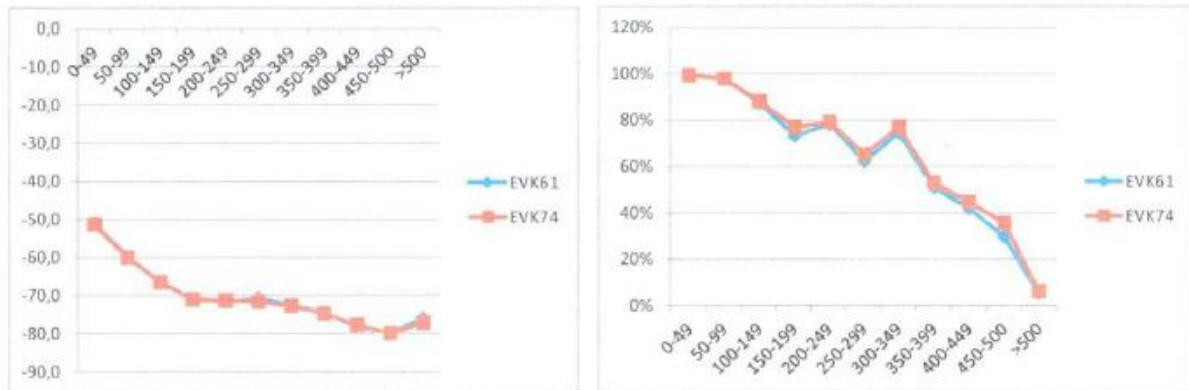


Fig. 25 - Max. transmission distance in the map for Lexus

The last tests of physical layer were RSSI measurement. First we measure RSSI in relation with distance between vehicles and received packets. Then we measure difference of RSSI between two states, when the sender was switched off and when it was switched on. Distance was calculated from GPS units, RSSI was measured by spectrometer and number of received packets was calculated with the help of network analyzer program Wireshark. All tests of physical layer were performed on the beginning of the project, so the values measured in this test weren't final, because how we can see, the percentage of received packets in distance below 300 m wasn't 100 %, so in this case system needed some improvements. In the case of distance higher than 500 m the percentage of received packets was only 5 - 6 % (which means packet loss 94 - 95 %). The detailed results are on the table (Tab. 6) and graph (Graph 3) (on the graph EVK61 =Toyota, EVK 74 = Lexus).

Distance [m]	RSSI [dBm]		Packets received [%]	
	Toyota	Lexus	Toyota	Lexus
0-49	-51,2	-51,6	99	99
50-99	-60,0	-60,3	97	98
100-149	-66,5	-66,7	87	88
150-199	-71,0	-71,2	73	77
200-249	-71,8	-71,5	78	79
250-299	-70,9	-71,8	62	65
300-349	-72,6	-72,9	74	77
350-399	-74,5	-74,8	51	53
400-449	-78,4	-77,9	42	45
450-500	-80,1	-80,0	30	36
500+	-75,0	-77,3	5	6

Tab. 6 - Influence of distance on RSSI and received packets



Graph 3 - Influence of distance on RSSI and received packets

On the picture (Fig. 26) below we can see difference in RSSI between the sender turned off (left picture) and sender turned on (right picture). This test was performed on the grounds of highway maintenance center Svojkovice. We can see that on the right picture (sender turned on) is maximum value (red) and average value (yellow) bigger than on the left picture. But we can see that there is some signal even if the sender is turned off. We didn't discover the source/sources of this signal. There are more possibilities of technologies, which are causing the interference in this reserved bandwidth.



Fig. 26 - RSSI in case of sender switched off (left) and switched on (right)

### 6.3.2. Data link layer

We were not able to perform test of QoS because of lack of communication units. Source MAC address test wasn't possible to perform because we didn't have access to the sittings of communication units. The last test from this layer, destination MAC address also wasn't performed because all messages were broadcasted.

### 6.3.3. Network and transport layer

To perform most tests of network and transport layer we needed three communication units so were not able to test these layers. We also were not able to perform GeoUnicast test, because in tested application was not any direct communication, all messages was broadcasted.

### 6.3.4. Session, presentation and application layer

In the last group of tests we focused on CAM and DENM messages. Unfortunately the test of HMI and related manners like delay or displaying and revoking the warning is not described

in this thesis, because HMI will be done after deadline of this work. On the following pictures is analysis of the damaged packets for Lexus (Tab. 7) and Toyota (Tab. 8). Analysis was done during the first tests of CAM messages so the number of damaged packets was high. Last test of CAM messages proved that 100 % of packets transferred properly. The number of damaged packets was not counted for DENM messages, because it was small number of them in the captured data, so the results would not be objective.

Time	Total packets	CAM packets	Damaged packets	% of damaged packets
12:02:37	17380	17380	14436	83,06%
13:41:35	766	765	630	82,35%
13:49:22	16415	10698	8595	80,34%
14:59:23	5153	5062	4197	82,91%
				average 82,17 %

Tab. 7 - Packet analysis for Lexus

Time	Total packets	CAM packets	Damaged packets	% of damaged packets
12:58:31	2663	2615	2079	79,50%
13:23:59	2283	2282	1513	66,30%
13:45:21	1660	1658	1244	75,03%
13:55:18	8511	9041	7389	81,73%
14:59:15	3318	3236	2680	82,82%
				average 77,08 %

Tab. 8 - Packet analysis for Toyota

For comparison we included the example of analysis of damaged CAM packets (some information is missing) (Fig. 27), CAM packets with false data from first test (Fig. 28) and CAM packets with one false value (Fig. 29) and DENM (Fig. 30) packets. On Fig. 31 is the latest CAM packet, without any false values. Below every CAM and DENM packet is the analysis of the same packet, what is wrong and what is correct. For this analysis was used program Wireshark.

Legend:

- **Green color** = entry ok
- **Yellow color** = entry ok, but with wrong value
- **Red color** = false entry



```

CAM
CAM
header
  protocolVersion: currentVersion (1)
  messageID: cam (2)
  stationID: 12340000
cam
  generationDeltaTime: unknown (58180)
  camParameters
    basicContainer
      stationType: heavyTruck (8)
      referencePosition
        latitude: unknown (498684750)
        longitude: unknown (138974265)
        positionConfidenceEllipse
          semiMajorConfidence: unavailable (4095)
          semiMinorConfidence: unavailable (4095)
          semiMajorOrientation: Unknown (2)
        altitude
          altitudeValue: unknown (933256)
          [Expert Info (warn/Protocol): size constraint: value too big: 933256 (-100000 .. 800001)]
            [Size constraint: value too big: 933256 (-100000 .. 800001)]
            [Severity level: warn]
            [Group: Protocol]
          altitudeConfidence: alt-100-00 (12)
          something unknown here [too long integer(per_normally_small_nonnegative_whole_number)]
    [Malformed Packet: CAM]
  [Expert Info (Error/Malformed): Malformed Packet (Exception occurred)]
    [Malformed Packet (Exception occurred)]
    [Severity level: Error]
    [Group: Malformed]

```

Fig. 27 - Damaged CAM packet

CAM

- CAM
    - header
      - protocolVersion: currentVersion (1)
      - messageID: cam (2)
      - stationID: 12340000
    - cam
      - generationDeltaTime: Unknown (58180)
      - camParameters
        - basicContainer
          - stationType: heavyTruck (8) – tests were performed with passengerCar (5), specialVehicle(10) ,not heavyTruck (8)
          - referencePosition
            - latitude: unknown (498684750) - 49°52'06.5"N
            - longitude: unknown (138974265) - 13°53'50.7"E (<https://goo.gl/xElh6n>)
          - positionConfidenceEllipse
            - semiMajorConfidence: unavailable (4095) – data not available
            - semiMinorConfidence: unavailable (4095) – data not available
            - semiMajorOrientation: unknown (2) – direction of the vehicle according to WGS84 (in all packets fixed value 2)
          - altitude
            - altitudeValue: Unknown (933256) – out of range (-100000..800001)
            - altitudeConfidence: alt-100-00 (12)
- Chyba – damaged packet (damaged data containers)

```

CAM
CAM
header
  protocolVersion: currentVersion (1)
  messageID: cam (2)
  stationID: 12340000
cam
  generationDeltaTime: Unknown (25924)
  camParameters
    basicContainer
      stationType: heavyTruck (8)
      referencePosition
        latitude: Unknown (498408216)
        longitude: Unknown (138165149)
        positionConfidenceEllipse
          semiMajorConfidence: unavailable (4095)
          semiMinorConfidence: unavailable (4095)
          semiMajorOrientation: Unknown (2)
        altitude
          altitudeValue: Unknown (933299)
          [Expert Info (warn/Protocol): Size constraint: value too big: 933299 (-100000 .. 800001)]
          altitudeConfidence: alt-000-10 (3)
      highFrequencyContainer: basicVehicleContainerHighFrequency (0)
      basicVehicleContainerHighFrequency
        heading
          headingValue: Unknown (3648)
          [Expert Info (warn/Protocol): Size constraint: value too big: 3648 (0 .. 3601)]
          headingConfidence: unknown (2)
        speed
          speedValue: Unknown (15872)
          speedConfidence: unknown (2)
          driveDirection: unknown (3)
        vehicleLength
          vehicleLengthValue: Unknown (912)
          vehicleLengthConfidenceIndication: unknown (7)
          vehicleWidth: Unknown (44)
        longitudinalAcceleration
          longitudinalAccelerationValue: unknown (298)
          [Expert Info (warn/Protocol): Size constraint: value too big: 298 (-160 .. 161)]
          longitudinalAccelerationConfidence: unknown (7)
        curvature
          curvatureValue: unknown (-15837)
          curvatureConfidence: onePerMeter-0-00002 (0)
          curvatureCalculationMode: unknown (3)
        yawRate
          yawRateValue: Unknown (20481)
          yawRateConfidence: Unknown (15)
          accelerationControl: 40 [bit length 7, 1 LSB pad bits, 0100 000. decimal value 32]
          lanePosition: hardShoulder (0)
        steeringWheelAngle
          steeringWheelAngleValue: unknown (80)
          steeringWheelAngleConfidence: unknown (128)
          [Expert Info (warn/Protocol): Size constraint: value too big: 128 (1 .. 127)]
        lateralAcceleration
          lateralAccelerationValue: Unknown (324)
          [Expert Info (warn/Protocol): Size constraint: value too big: 324 (-160 .. 161)]
          lateralAccelerationConfidence: unknown (32)
        verticalAcceleration
          verticalAccelerationValue: unknown (-9)
          verticalAccelerationConfidence: unknown (96)
      lowFrequencyContainer: basicVehicleContainerLowFrequency (0)
      basicVehicleContainerLowFrequency
        vehicleRole: default (0)
        exteriorLights: 01 [bit length 8, 0000 0001 decimal value 1]
        pathHistory: 0 items
      specialVehicleContainer: publicTransportContainer (0)
      publicTransportContainer
        ...0 .... embarkationStatus: False

```

Fig. 28 - Complete CAM packet with errors

CAM

- CAM
  - header
    - protocolversion: currentVersion (1)
    - messageID: cam (2)
    - stationID: 12340000
  - cam
    - generationDeltaTime: Unknown (25924)
  - camParameters
    - basicContainer
      - stationType: heavyTruck (8) – tests were performed with passengerCar (5) or specialVehicle(10), not heavyTruck (8)
    - referencePosition
      - latitude: unknown (498408216) - 49°50'27.0"N
      - longitude: unknown (138165149) - 13°48'59.5"E (<https://goo.gl/6aYOhe>)
    - positionConfidenceEllipse
      - semiMajorConfidence: unavailable (4095) – data not available
      - semiMinorConfidence: unavailable (4095) – data not available
      - semiMajorOrientation: unknown (2) - direction of the vehicle according to WGS84 (in all packets fixed value 2)
    - altitude
      - altitudeValue: Unknown (933299) – out of range (-100000..800001)
      - altitudeConfidence: alt-000-10 (3)
  - highFrequencyContainer: basicvehicleContainerHighFrequency (0)
  - basicvehicleContainerHighFrequency
    - heading
      - headingValue (3648) – out of range (-0..3601)
      - headingConfidence: Unknown (2)
    - speed
      - speedvalue: Unknown (15872) – 158,72 m/s = 571,392 km/h !!!
      - speedConfidence: Unknown (2)
      - driveDirection (3) – out of range (0..2)
    - vehicleLength
      - vehicleLengthValue: Unknown (912) – length of vehicle 91,2 m
      - vehicleLengthConfidenceIndication: Unknown (7) – out of range (0..4)
      - vehicleWidth: Unknown (44) – width of vehicle 4,4 m
    - longitudinalAcceleration
      - longitudinalAccelerationValue: Unknown (298) – out of range (-160..161)
      - longitudinalAccelerationConfidence: Unknown (7)
    - curvature
      - curvatureValue: Unknown (-15837) – value fixed in all packets
      - curvatureConfidence: onePerMeter-0-00002 (0)
      - curvatureCalculationMode: Unknown (3) – out of range (0..2)
    - yawRate
      - yawRateValue: Unknown (20481) – value fixed in all packets
      - yawRateConfidence: Unknown (15) – out of range (0..8)
      - accelerationControl: 40 – out of range (0..7)
      - lanePosition: hardShoulder (0)
    - steeringWheelAngle
      - steeringWheelAngleValue: Unknown (80)
      - steeringWheelAngleConfidence: Unknown (128) – out of range (1..127)
    - lateralAcceleration
      - lateralAccelerationValue: Unknown (324) – out of range (-160..160)
      - lateralAccelerationConfidence: Unknown (32)
    - verticalAcceleration

```

    verticalAccelerationValue: Unknown (-9)
    verticalAccelerationConfidence: Unknown (96)
  - lowFrequencyContainer: basicVehicleContainerLowFrequency (0)
    - basicVehicleContainerLowFrequency
      vehicleRole: default (0)
      exteriorLights: 1 -1 indicates that vehicle has turned on main beam headlights (during daytime)
      pathHistory: 0 items
  - specialVehicleContainer: specialTransportContainer (0)
    - specialTransportContainer
      embarkationStatus: False

CAM
CAM
  header
    protocolVersion: currentVersion (1)
    messageID: cam (2)
    stationID: 1
  cam
    generationDeltaTime: Unknown (34644)
    camParameters
      basicContainer
        stationType: specialVehicles (10)
        referencePosition
          latitude: Unknown (500564450)
          longitude: Unknown (145387883)
        positionConfidenceEllipse
          semiMajorConfidence: unavailable (4095)
          semiMinorConfidence: unavailable (4095)
          semiMajorOrientation: Unknown (2)
        altitude
          altitudeValue: Unknown (24887)
          altitudeConfidence: unavailable (15)
      highFrequencyContainer: basicVehicleContainerHighFrequency (0)
        basicVehicleContainerHighFrequency
          heading
            headingValue: unknown (917)
            headingConfidence: unavailable (127)
          speed
            speedValue: unknown (1183)
            speedConfidence: unavailable (127)
            driveDirection: unavailable (2)
          vehicleLength
            vehicleLengthValue: unknown (40)
            vehicleLengthConfidenceIndication: unavailable (4)
            vehicleWidth: unknown (20)
          longitudinalAcceleration
            longitudinalAccelerationValue: unavailable (161)
            longitudinalAccelerationConfidence: unavailable (102)
          curvature
            curvatureValue: unavailable (30001)
            curvatureConfidence: unavailable (7)
            curvatureCalculationMode: unavailable (2)
          yawRate
            yawRateValue: unavailable (32767)
            yawRateConfidence: unavailable (8)

```

Fig. 29 - Complete CAM packet with few errors

## CAMCAM

- header
  - protocolversion: currentVersion (1)
  - messageID: cam (2)
  - stationID: 1
- cam
  - generationDeltaTime: Unknown (34644)
- camParameters
  - basicContainer
    - stationType: specialVehicles (10) referencePosition
    - latitude: unknown (500564450) - 50°03'23.2"N
    - longitude: unknown (145387883) - 14°32'19.6"E (<https://goo.gl/jfxXZ4>)
    - positionConfidenceEllipse
      - semiMajorConfidence: unavailable (4095) – data not available
      - semiMinorConfidence: unavailable (4095) – data not available
      - semiMajorOrientation: unknown (2) - direction of the vehicle according to WGS84 (in all packets fixed value 2)
    - altitude
      - altitudeValue: Unknown (24887)
      - altitudeConfidence: 15 – data not available
  - highFrequencyContainer: basicvehicleContainerHighFrequency (0)
    - basicvehicleContainerHighFrequency
      - heading
        - headingValue (917)
        - headingConfidence: Unknown (127) – data not available
      - speed
        - speedvalue: Unknown (1183) – 11,83 m/s = 42,6 km/h
        - speedConfidence: Unknown (127) – data not available
        - driveDirection (2) – data not available
      - vehiclelength
        - vehicleLengthValue: Unknown (40)
        - vehicleLengthConfidenceIndication: Unknown (4) – data not available
        - vehicleWidth: Unknown (20)
      - longitudinalAcceleration
        - longitudinalAccelerationValue: Unknown (161) – data not available
        - longitudinalAccelerationConfidence: Unknown (102) – data not available
      - curvature
        - curvatureValue: Unknown (30001) – data not available
        - curvatureConfidence: (7) - data not available
        - curvatureCalculationMode: Unknown (2) - data not available
      - yawRate
        - yawRateValue: Unknown (32767) – data not available
        - yawRateConfidence: Unknown (8) – data not available

```

DENM
├── header
│   ├── protocolVersion: currentVersion (1)
│   ├── messageID: denm (1)
│   └── stationID: 1
├── denm
│   ├── management
│   │   ├── actionID
│   │   │   ├── originatingStationID: 1
│   │   │   ├── sequenceNumber: 3
│   │   │   ├── detectionTime: 16656d1a5c00 [bit length 42, 6 LSB pad bits, 0001 0110 0110 0101 0110 1101 0001 1010 0101 1100 00.. .... decimal value 384763718000]
│   │   │   └── referenceTime: 16656d1b2040 [bit length 42, 6 LSB pad bits, 0001 0110 0110 0101 0110 1101 0001 1011 0010 0000 01.. .... decimal value 384763718785]
│   │   └── eventPosition
│   │       ├── latitude: Unknown (497933016)
│   │       ├── longitude: Unknown (137338066)
│   │       └── positionConfidenceEllipse
│   │           ├── semiMajorConfidence: unavailable (4095)
│   │           ├── semiMinorConfidence: unavailable (4095)
│   │           └── semiMajorOrientation: unavailable (3601)
│   │       └── altitude
│   │           ├── altitudeValue: Unknown (46811)
│   │           ├── altitudeConfidence: unavailable (15)
│   │           ├── relevanceDistance: lessThan50m (0)
│   │           ├── relevanceTrafficDirection: allTrafficDirections (0)
│   │           ├── validityDuration: Unknown (7200)
│   │           ├── transmissionInterval: Unknown (1000)
│   │           └── stationType: unknown (0)
│   ├── situation
│   │   ├── informationQuality: unavailable (0)
│   │   └── eventType
│   │       ├── causeCode: roadworks (3)
│   │       └── subCauseCode: 0
│   ├── location
│   │   ├── traces: 1 item
│   │   │   ├── item 0
│   │   │   │   ├── pathHistory: 1 item
│   │   │   │   │   ├── item 0
│   │   │   │   │   └── pathPoint
│   │   │   │   │       └── pathPosition
│   │   │   │   │           ├── deltaLatitude: unavailable (131072)
│   │   │   │   │           ├── deltaLongitude: unavailable (131072)
│   │   │   │   │           └── deltaAltitude: unavailable (12800)
│   │   └── alacarte
│   │       ├── roadworks
│   │       └── speedLimit: unknown (80)

```

Fig. 30 - Complete DENM packet

#### DENM

- header
  - protocolVersion: currentVersion (1)
  - messageID: denm (1)
  - stationID: 1
- denm
  - management
    - actionID
      - originatingStationID: 1
      - sequenceNumber: 3
      - detectionTime: 384763718000
      - referenceTime: 384763718785
    - eventPosition
      - latitude: Unknown (497933016)
      - longitude: Unknown (137338066) - <https://goo.gl/NEhxxU>
    - positionConfidenceEllipse
      - semiMajorConfidence: unavailable (4095) - data not available
      - semiMinorConfidence: unavailable (4095) - data not available
      - semiMajorOrientation: unavailable (3601) - data not available
    - altitude
      - altitudeValue: Unknown (46811)
      - altitudeConfidence: Unavailable (15) - data not available
      - relevanceDistance: lessThan50m (0)
      - relevanceTrafficDirection: allTrafficDirection (0)
      - validityDuration: Unknown (7200)
      - transmissionInterval: Unknown (1000)
      - stationType: unknown (0)
    - situation
      - informationQuality: unavailable (0) - data not available
    - eventType



CAM

- CAM
  - header
    - protocolversion: currentVersion (1)
    - messageID: cam (2)
    - stationID: 1
  - cam
    - generationDeltaTime: Unknown (37060)
  - camParameters
    - basicContainer
      - stationType: specialVehicles (10)
      - referencePosition
        - latitude: unknown (500587850)
        - longitude: unknown (145190416) - <https://goo.gl/QTK1Ei>
        - positionConfidenceEllipse
          - semiMajorConfidence: unavailable (4095) – data not available
          - semiMinorConfidence: unavailable (4095) – data not available
          - semiMajorOrientation: unknown (2725)
        - altitude
          - altitudeValue: Unknown (30536)
          - altitudeConfidence: 15 – data not available
    - highFrequencyContainer: basicVehicleContainerHighFrequency (0)
    - basicVehicleContainerHighFrequency
      - heading
        - headingValue (2725)
        - headingConfidence: Unknown (127) – data not available
      - speed
        - speedValue: Unknown (10) – 0,1 m/s = 0,36 km/h
        - speedConfidence: Unknown (127) – data not available
        - driveDirection (2) – data not available
      - vehicleLength
        - vehicleLengthValue: Unknown (40)
        - vehicleLengthConfidenceIndication: Unknown (4) – data not available
        - vehicleWidth: Unknown (20)
      - longitudinalAcceleration
        - longitudinalAccelerationValue: Unknown (161) – data not available
        - longitudinalAccelerationConfidence: Unknown (102) – data not available
      - curvature
        - curvatureValue: Unknown (30001) – data not available
        - curvatureConfidence: (7) - data not available
        - curvatureCalculationMode: Unknown (2) - data not available
      - yawRate
        - yawRateValue: Unknown (32767) – data not available
        - yawRateConfidence: Unknown (8) – data not available



## **6.4. Results**

Because of reasons mentioned above, we were not able to perform some tests. But the main tests were performed successfully and in this chapter we would like to comment in detail the results of tests. Please take into consideration that the project is still running and most of the problems, which we found in our tests and analysis, were or will be resolved.

### **6.4.1. Physical layer tests**

The very first test of V2X systems in our project was focused on the frequency allocation of signals transmitted by communication units. The test was successful and we found out that on the frequency 5850 MHz – 5925 MHz is some signal transmitted with RSSI about - 85 dBm, which is enough to connect two devices. So we could proceed to following tests.

Next test was a test of transmission range. Progress of the test is described in chapter above. The value recommended by C2C communication consortium of transmission range is 300 m in LOS conditions. This value was even exceeded in LOS conditions; we could transfer packets to 500 m distance. On the other hand in non-LOS conditions the transmission range dropped to 100 m (in case of Toyota) or 150 m in case of Lexus. In the case of deployment of V2X systems is needed to mount these sections of highways by RSU, because the vehicle with velocity 130 km/h travels 100 m in 3 seconds and this time is not sufficient for driver to react properly on the upcoming events.

Then we tested influence of range on RSSI and packet loss (received packets). This test was performed only in beginning of project, during the later tests was monitoring of the packet loss included in the tests of CAM and DENM messages. These test showed us that value of RSSI is sufficient even in the distances higher than 500 m, where is possible to achieve RSSI about 75 – 77 dBm, which is not that far from the value of RSSI 74 – 75 dBm in 350m distance. On the other hand we found out that packet loss is increasing very fast with the increasing distance between communication units. From almost 0 % in very close range to more than 95 % in distances higher than 500 m. Fortunately this was fixed by changing of settings and in the next tests we didn't have any problems with loss of packets.

The last test of physical layer was rather informative for us. We decided to check, if there is something else transmitting signals on the frequency reserved for V2X communication. We discovered by spectrometer measuring that on reserved frequency is still some traffic, even when communication units were turned off. We didn't discover the source of these signals, we can only guess, what is causing it. It could be 5 GHz Wi-Fi, because this Wi-Fi is using

for outside applications bandwidth 5 470 MHz – 5 725 MHz, which is not that far from ITS bandwidth. Another possibility is the near toll gate, which is communicating with the vehicles on frequency 5,8 GHz. It could also be Ground penetrating radar or Wall probing radar, which are also using near frequencies. The last possibility is so called ISM applications. Industrial, Scientific and Medical applications have their own reserved band near the ITS band. Example of devices transmitting in this band is cordless phone or balloons (for balloon and ground communication).

#### 6.4.2. Session, presentation and application layer tests

Tests of last three layers were focused on CAM and DENM messages. During the analysis of the packets, from the first data capture, in the Wireshark we found out that there was transmitted a high number of damaged packets. Percentage of damaged packets was 82 % for Lexus and 77 % for Toyota. Analysis of damaged CAM packet is shown above. Damaged packets were not sufficient for transporting information because they didn't contain mandatory data entities like speed or acceleration. From the same data capture is provided complete CAM packet, but it contained so many errors, that the V2X system couldn't work in a real world. Errors which we found in the CAMs packets from the first data capture are stated below in Tab. 9

Data element	Measured value	Comment
semiMajorOrientation	2	Fixed value in all packets
altitudeValue	933299	Out of range
headingValue	3648	Out of range
driveDirection	3	Out of range
vehicleLengthConfidenceIndication	7	Out of range
longitudinalAccelerationValue	298	Out of range
curvatureValue	-15837	Fixed value in all packets
curvatureCalculationMode	3	Out of range
yawRateValue	20481	Fixed value in all packets
yawRateConfidence	15	Out of range
accelerationControl	40	Out of range
steeringWheelAngleConfidence	128	Out of range
lateralAccelerationValue	324	Out of range

Tab. 9 - Errors in CAM messages

The second data capture showed better results than the first one. The percentage of damaged packets was 0 % (all packets were correct) and the packets contained less errors than the previous one. DENM packets were almost perfect, although it contained only the

mandatory data elements, but it doesn't affect operability in the case of application of roadworks warning. CAM packets weren't that good, but it was major improvement, it could work during deployment, but with limited operation.

In the last data capture with CAM packets were not found any crucial errors. But a high number of data elements were still not available (this problem is present since beginning of the testing). Below we can found Tab. 10 of unavailable data elements in the last data capture. This was caused by testing of V2X systems with vehicle that wasn't equipped with CAN bus. Cooperative systems can operate with vehicles without CAN bus but it doesn't have access to some information (yellow lines in the analysis). Therefore we are waiting on the next tests, which will be performed after deadline of this work with car equipped with CAN bus.

Unavailable data element
semiMajorConfidence
semiMinorConfidence
altitudeConfidence
headingConfidence
speedConfidence
driveDirection
vehicleLengthConfidenceIndication
longitudinalAccelerationValue
longitudinalAccelerationConfidence
curvatureValue
curvatureConfidence
curvatureCalculationMode
yawRateValue
yawRateConfidence

Tab. 10 - Unavailable data elements in CAM messages

## 7. Conclusion

In the thesis were introduced cooperative systems, how they function, what they consist of, what are expected benefits from their deployment or what are problems connected to V2X systems. We demonstrate function of these systems on the different projects which took place in European Union with focus on Czech Republic. Especially important are standards from ITS because they ensure that vehicles from different manufacturers can interoperate between themselves and also they works in this area like a manual for manufacturers how to maintain processes and functions of cooperative systems. Possibilities to verify V2X systems were also introduced. Taking into account all this information we could move to goal of the thesis

Main goal of the thesis was designing the methodology for verifying cooperative systems and then according to this methodology test cooperative systems within the project Implementation of cooperative systems in the environment of Czech Republic. The methodology was designed with focus on the valid ITS standards and technical parameters of cooperative systems. The most important standards for us are published by ETSI (in this case). They put a lot of effort to produce high quality ITS standards to reduce possible future problems with interoperability. If the implemented system pass all tests within the methodology, it won't have any problems to cooperate with cooperative systems from any other manufacturer, which is important in case of deployment these systems in Europe. Conformance, interoperability and even the ability of signal to carry information is tested.

Testing is divided to layers according to OSI model from the lowest one (physical layer) to the top one (application layer). For the testing is important to have full access to the communication units, which we didn't have, so we were not able to perform some tests and we had to trust the employees of company, which were implementing the cooperative systems, that the layers we skipped were operating properly. We were focusing just on the transmission function of cooperative systems. Privacy protection (preserving anonymity of the user) and security (preventing malicious usage of V2X systems) weren't tested because it requires much more extensive testing and it wasn't part of the project.

Designed methodology had to be modified because of numerous reasons mentioned above. Tests of physical layer took one day of measuring at the complex of Highway maintenance center Svojkovice. Results from the tests of physical layer were good; we confirmed by these tests that the communication units are able to communicate between each other on the physical layer. During the tests of physical layer we encountered only one problem, that there was present signal from the unknown source, which was also transmitted on the frequency

reserved for ITS (5,850 GHz – 5,925 GHz). This problem requires assistance with the Czech Telecommunication Office, only this office can penalize them for transmitting in the reserved frequency and make them to move to another frequency.

So far there were three rounds of CAM and DENM messages testing, each took one day. Our first test of messages was executed in July 2015. During these data captures were recorded thousands of packets and other information important for proper analysis. The results from first tests of CAM messages were worse than expected; there was high number of damaged packets and also high number of mistakes in data elements. We provided detailed analysis of errors we found to the company, which was implementing V2X systems.

Unfortunately, we had to wait to March 2016 for the second iteration of messages testing. In the second testing were also present only CAM messages, but these messages were almost completely fixed. There were problem with one data element and few statistics data elements were unavailable, that was caused by missing connection between vehicle and OBU because vehicle was not equipped with the CAN bus. Third iteration of tests was even more successful, only the statistics data elements (e.g. confidences of values) missed in the CAM messages because of the same reason. Also in this so far last iteration were present DENM messages. In these messages was only one problem, the same one like in the CAM messages - unavailable statistics data elements. How we stated above, the project is still running and the final results will be available after deadline of this thesis. This test proved that vehicles can interchange information in CAM and DENM messages. Performed tests and analyzed results proved that methodology designated in this thesis can be used for verification of cooperative systems with success. Tested V2X system works properly with some minor problems, which will be resolved, and so far is working according to published ITS standards.

## 7.1. Future work and costs for testing

The methodology for testing V2X systems has to cover also the security and the privacy aspects. Incorporating these aspects into testing methodology is considered as essential and requires additional analysis. Without testing that system fulfill given criteria regarding privacy and security is unthinkable that users will accept these systems in their cars, systems that can spy on them or be vulnerable to malicious usage, if they are badly designed. Unfortunately testing these aspects is more difficult than testing the transmission ability because it involves more elements (connection to the server processing the data, server itself or the certification and verification authority).

It would be also interesting to compare results of testing according to this methodology between V2X system designed in Europe, like in our case, and system designed in United States. There are some dissimilarity between the architectures of systems from US and Europe, as they are standardized by different bodies (mainly ETSI in case of Europe and mainly IEEE in case of US).

As the last point of thesis I want to discuss financial costs of performing testing of V2X systems according to introduced methodology. We assume that we already have at least three vehicles (all of them equipped with CAN bus) and the same number of On Board Units with antennas and HMI, which we want to test. Used software for analysis of network traffic (Wireshark) is "free". So the only costs are measuring equipment (spectrometer and GPS units) and costs for human labor. Professional spectrometer costs around 1500 € and GPS receiver with sufficient accuracy (close to 1 m) costs 500 €. Price for labor of technician is different across European countries and the number of hours measuring and analyzing is also different from case to case. In an ideal case testing according to "full" methodology takes about 14 days for three people. From this we can easily estimate cost for testing already implemented V2X system in different countries.

## 8. Reference

- [1] BĚLINOVÁ, Z.: *Lectures at Faculty of transportation sciences*. CTU in Prague, Faculty of transportation sciences. Telematické soustavy: Kooperativní systémy. 2011.
- [2] eSafety Workshop 2006, Fritz Busch, *Traffic Management now and in 2020 – a vision*
- [3] PÍPA, M.: *Kooperativní systémy v dopravě* [online]. [cit. 2016-01-04]. Available at WWW: <http://www.cdv.cz/kooperativni-systemy-v-doprave/>
- [4] PRAVDA, I.: *Lectures at Faculty of electrical engineering*. CTU in Prague, Faculty of electrical engineering. Telekomunikační sítě páteřní a přístupové, datové spoje a rozhraní.
- [5] Sichere Intelligente Mobilität Testfeld Deutschland [online]. [cit. 2016-01-04]. Available at WWW: <http://www.simtd.de/>
- [6] ŠROTÝŘ, M.: *Alternativní telekomunikační řešení n bázi IEEE802.11 v ITS aplikacích*. CTU in Prague, Faculty of transportation sciences. 2007. Supervisor of bachelor's thesis Tomáš Zelinka.
- [7] KAREL, M.: *Nové trendy v technologiích DSRC pro dopravní aplikace*. CTU in Prague, Faculty of transportation sciences. 2010. Supervisor of bachelor's thesis Tomáš Zelinka.
- [8] PŘIBYL, P., SVÍTEK, M.: *Intelligentní dopravní systémy*. 1. edition. Prague, Publishing house BEN – technická literatura, 2001. ISBN 80-7300-029-6.
- [9] Co-operative Systems for Intelligent Road Safety [online]. [cit. 2016-01-04]. Available at WWW: <http://www.coopers-ip.eu>
- [10] Cooperative Mobility Systems and Services for Energy Efficiency [online]. 2014 [cit. 2016-01-04]. Available at WWW: <http://www.ecomove-project.eu/>
- [11] Connecting vehicles for safe, comfortable and green driving on European roads. [online]. [cit. 2016-01-04]. Available at: <http://drive-c2x.eu/>
- [12] Compass4d [online]. [cit. 2016-01-04]. Available at: <http://www.compass4d.eu/>
- [13] Intelligent transport systems in action – Pilot testing of project BaSIC. [online]. 2013 [cit. 2016-01-04]. Available at WWW: <http://www.czechspaceportal.cz/4-sekce/veda-a-vyzkum/vybrane-aktuality-a-clanky-3/inteligentni-dopravni-systemy-v-akci---pilotni-testovani-projektu-basic.html>
- [14] LOKAJ, Z.: *Lectures at Faculty of transportation sciences*. CTU in Prague, Faculty of transportation sciences. Telekomunikace 2013
- [15] DVOŘÁK, F.: *Auta si o koloně poví tichou poštou, testují ji na obchvatu Prahy*. [online]. 2013 [cit. 2016-01-04]. Available at: [http://auto.idnes.cz/auta-komunikace-0ix-/automoto.aspx?c=A131112\\_170430\\_automoto\\_fdv](http://auto.idnes.cz/auta-komunikace-0ix-/automoto.aspx?c=A131112_170430_automoto_fdv)
- [16] ZELINKA, T., SVÍTEK, M.: *Telekomunikační řešení pro informační systémy síťových odvětví*. 1. edition Prague, Grada Publishing, a.s., 2009. ISBN 978-80-247-3232-9.

- [17] eCall (automatic emergency call). [online]. [cit. 2016-01-04]. Available at: <http://www.czechspaceportal.cz/3-sekce/its---dopravni-telematika/ecall/>
- [18] SVÍTEK, M., ZELINKA, T., VOTRUBA, Z., LOKAJ, Z., BUREŠ, P., BĚLINOVÁ, Z., ŠROTÝŘ, M.: *Studie aplikací kooperativních systémů v prostředí městské aglomerace se zaměřením na možnosti jejich využití v hl.m. Praze*. CTU in Prague, Faculty of transportation sciences. 2012. Version 3.00.
- [19] BAJERS, B.: *Network Planning of Road Side Units in the Intelligent Transport System Domain*. Aalborg Universitet, Department of Electronic Systems, 2012
- [20] NAVRATIL, G.: *Lectures at Fachhochschule Technikum Wien*. UAS in Wien, Fachhochschule technikum Wien. Geographic Information Systems: Standards, 2015.
- [21] European Committee for Standardization [online] . [cit. 2016-01-04]. Available at WWW: <https://www.cen.eu>
- [22] European Telecommunications standards institute [online] . [cit. 2016-01-04]. Available at WWW: <https://www.etsi.org>
- [23] ETSI TS 102 687 v1.1.1 - Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range
- [24] ETSI TS 102 724 v 1.1.1 - Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band
- [25] ETSI ES 202 663 v1.1.0 - European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band
- [26] IEEE 802.11 – Wi-Fi
- [27] IEEE 802.3. – Ethernet
- [28] ISO 11898-1:2015 - Road vehicles - Controller area network (CAN)
- [29] ETSI EN 302 636-1/2/3 – Vehicular communications; GeoNetworking
- [30] ETSI EN 302 636-4-1 v.1.2.0 - Vehicular communications; GeoNetworking
- [31] ETSI EN 302 636-5-1 v1.2.0 - Vehicular communications; GeoNetworking
- [32] ETSI EN 302 931 v1.0.0 – Vehicular communications; Geographical Area Definition
- [33] ETSI EN 302 665 v1.1.1 – Communications architecture
- [34] ETSI EN 102 894-1 v1.1.1 - Users and applications requirements
- [35] ETSI EN 302 637-2 v1.3.1 – Vehicular communications; Basic set of applications; Specification of cooperative awareness basic service
- [36] ETSI EN 302 637-3 v1.2.1 – Vehicular communications; Basic set of applications; Specification of decentralized environmental notification basic service
- [37] ETSI EN 102 894-2 – v1.2.1 - Users and applications requirements; Applications and facilities layer common data dictionary



- [38] ETSI TS 102 637-1 v1.1.1 – Vehicular communications; Basic set of applications; functional requirements and ETSI TS 102 638-1 v1.1.1 – Vehicular communications; Basic set of applications; definitions
- [39] ETSI EN 302 895 v1.1.1 – Vehicular communications; Basic set of applications; Local dynamic map
- [40] ETSI TS 101 539-1 v1.1.1 – V2X applications; Road hazard signaling application requirements specification
- [41] ETSI EG 202 798 v1.1.1. – Testing; Framework for conformance and interoperability testing
- [42] ETSI TS 102 868-1/2/3 V1.1.1 – Testing; Conformance test specification for cooperative awareness message; Part 1; Part 2 and Part 3
- [43] ETSI TS 102 869-1/2/3 V1.4.1– Testing; Conformance test specification for Decentralized Environmental Notification Messages; Part 1; Part 2 and Part 3
- [44] ETSI TS 102 870-1/2/3 V1.1.1– Testing; Conformance test specification for GeoNetworking basic transport protocol (BTP); Part 1; Part 2 and Part 3
- [45] ETSI TS 102 871-1/2/3 V1.1.1– Testing; Conformance test specification for GeoNetworking ITS-G5; Part 1; Part 2 and Part 3
- [46] BALDESSARI, R., BOEDEKKER, B., DEGENER, M., FESTAG, A., FRANZ, W., CHRISTOPHER KELLUM, C., KOSCH, T., KOVACS, A., LENARDI, M., MENIG, C., PEICHL, T., ROECKL, M., SEEBERGER, D., STRASSBERGER, M., STRATIL, H., VOEGEL, H.-J., WEYL, B., ZHANG, W.: Car-2-car communication consortium - manifesto, 2007
- [47] BOSSOM, R., BRIGNOLO, R., ERNST, T., EVENSEN, K., FRÖTSCHER, A., HÖFS, W., JÄÄSKELÄINEN, J., JEFTIC, Z., KOMPFFNER, P., KOSCH, T., KULP, I., KUNG, A., MOKADDEM, A.-K., SCHALK, A., UHLEMANN, E., WEWETZER, C.: European ITS communication architecture — Overall framework — Proof of concept implementation. Technical report, EC Information Society Technologies Programme, 2010
- [48] Google maps [online] [cit. 2016-01-04]. Available at WWW: <https://www.google.cz/maps>
- [49] OASIS TAB Wiki, Testing policy [online] [cit. 2016-01-04]. Available at WWW: <https://wiki.oasis-open.org/tab/TestingPolicy>