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Analysis of V2X Performance and Rollout Status with a Special Focus on Austria

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Abstract

Vehicle to Everything (V2X) has the potential to make road traffic safer and further advance autonomous driving. The goal of this work is to evaluate the performance and roll-out status of V2X in real life. Previous work shows very different results, both with simulations and with real hardware. To evaluate the performance of V2X in real life, six test runs were performed: (i) three scenarios to evaluate official V2X projects, (ii) two scenarios to evaluate V2X performance under optimal conditions, and (iii) one scenario to evaluate the VW Golf 8. The data was collected using a V2X monitor and analyzed in order to answer three questions: (i) the roll-out status, (ii) the difference between practical applications and specification and (iii) the performance of V2X. The results show that V2X works well and meets expectations, but the roll-out is slow.

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Acronyms

3GPP 3rd Generation Partnership Project 37

5G Fifth Generation 21, 39, 40

BSM Basic Safety Message 28

BSS Basic Service Set 31

BTP Basic Transport Protocol 33

C-ITS Cooperative Intelligent Transport Systems 30–36, 38, 39, 46, 49, 55, 58, 67, 68, 72

C-V2X Cellular Vehicle to Everything 21, 22, 25, 37–40, 71, 72

CA Cooperative Awareness 34

CAM Cooperative Awareness Message 27–29, 33, 34, 36, 49, 50, 53, 55, 57–59, 65, 67, 68, 71

CAN Controller Area Network 41

CBR Channel Busy Ratio 36, 39

CL Channel Load 36

CR Channel Occupancy Ratio 39

D2D Device-to-Device 37, 38

DCC Decentralized Congestion Control 27, 33, 35, 36

DENM Decentralised Environmental Notification Message 28, 29, 33, 36, 47, 50, 53, 57–59, 65, 67, 68, 70, 71

ETSI European Telecommunications Standards Institute 13, 23, 27–39, 68, 71

GPS Global Positioning System 41, 55

GUI Graphic User Interface 41

HF High Frequency 28

ID identifier 28

IEEE Institute of Electrical and Electronics Engineers 30–32

ISO International Organization for Standardization 30

ITS Intelligent Transport System 13, 28–32, 34, 41, 42, 49, 50, 53

ITS-G5 Intelligent Transport Systems - 5.9 GHz Vehicular Ad Hoc Network Physical Layer 21–23, 25, 30, 32, 39, 40, 67–69, 71, 72

ITS-S Intelligent Transport System - Station 30, 35, 36, 46

IVIM In Vehicle Information Message 29, 50, 53, 58, 67, 71

LF Low Frequency 28

LLC Logical Link Control 33

LTE Long Term Evolution 21, 37–41, 71

MAC Media Access Control 33, 67

MAP Map Data 30, 53, 67, 72

MAPEM Map Data Extended Message 30, 55, 71

NR New Radio 39, 40

OBU On Board Unit 30, 41

OCB Outside the Context of a BSS 31, 32

OFDM Orthogonal Frequency-Division Multiplexing 31, 32

OSI Open Systems Interconnection model 32

PC5 Proximity-based Communication 5 37, 38

PDU Protocol Data Unit 28–30, 50

POI Point of Interest 47, 49, 53, 55

ProSe Proximity Services 38

PRR Package Receive Ratio 40

QAM Quadrature Amplitude Modulation 39

QPSK Quadrature Phase Shift Keying 39

RAT Radio Access Technology 25, 30, 37

RLAN Radio Local Area Network 33

RSU Road Side Unit 23, 27, 30, 37, 41, 45–51, 53, 55–59, 63–65, 67–71

SAE Society of Automotive Engineers 27, 29

SCI Sidelink Control Information 39

SPaT Signal Phase and Timing 30, 53, 67, 72

SPaTEM Signal Phase and Timing Extended Message 30, 55, 71

SREM Signal Request Extended Message 30, 67

SRM Signal Request Message 30

SSEM Signal Status Extended Message 30, 53, 67

SSH Secure Shell 43

SSM Signal Status Message 30

TB Transport Block 39

TC Traffic Class 36

TDC Transmit Datarate Control 35

TPC Transmit Power Control 35

TRC Transmit Rate Control 35

UDP User Datagram Protocol 33, 43

UE User Equipment 37–40

USB Universal Serial Bus 41

V2I Vehicle to Infrastructure 25, 37

V2N Vehicle to Network 26, 37

V2P Vehicle to Pedestrian 26

V2V Vehicle to Vehicle 25

V2X Vehicle to Everything 5, 13, 21–23, 25–27, 30, 31, 37–41, 45–49, 55, 65, 67, 70–72

1 Introduction

Traffic accidents are still a significant problem. In the EU, for example, 18,800 people died in road accidents in 2020. This means that every half an hour, a person dies on the road in the EU [1]. Even though those numbers are going down over the last decades, the EU set the goal to cut deaths on the road by 50% between 2010 and 2030 [2]. To achieve this goal, new cars are equipped with many advanced technologies, such as distance sensors, blind-spot detection, and lane change assistant, to increase road safety. To reduce the fatalities even further, V2X could be a leading technology. V2X enables vehicles to link and exchange information with each other, as well as infrastructure, pedestrians, and the internet. With V2X awareness can be raised beyond the capabilities of on board sensors to prevent accidents, such as rear-end collisions at the end of traffic jams on the highway. Additionally, warnings from overhead displays could be displayed for the driver, thereby increasing safety and driving experience.

V2X can also be an important building block for the steady progress of automated driving. While many new high-end cars now come with traffic sign recognition, it still has significant problems recognizing additional information on road signs and crossed-out signs. Road signs equipped with V2X could bring much progress to autonomous driving development. Furthermore, V2X can help make complicated and confusing intersections more understandable for autonomous driving. This is achieved by describing the intersection layout, including all the lanes and the status of the traffic lights. Lastly, V2X can warn of hazardous events and communicate priority at intersections.

For both of these use cases — cooperative awareness and traffic information — V2X is a key issue as it enables vehicles to communicate with each other and the environment. V2X works on broadcast-based, wireless packets that can be received and sent by vehicles, infrastructure, by global networks such as the internet, and in the future possibly by pedestrians. Currently, there are two V2X technologies fighting for the market: Intelligent Transport Systems - 5.9 GHz Vehicular Ad Hoc Network Physical Layer (ITS-G5), which is based on the WiFi technology, and Cellular Vehicle to Everything (C-V2X), which is based on the Long Term Evolution (LTE) technology (and subsequently on the Fifth Generation (5G) technology).

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[1] `https://ec.europa.eu/commission/presscorner/detail/en/ip_21_1767` accessed 21.04.2021

[2] `https://ec.europa.eu/transport/media/news/2020-06-11-road-safety-statistics-2019_en` accessed 20.03.2021

1.1 Motivation and Goals

Although the use of V2X is starting to grow, it is still challenging to find information. Additionally, there are currently two competing technologies, ITS-G5 and C-V2X, and it is not yet decided which technology will prevail. Hence, this thesis wants to give the theoretical background on both implementations, focusing on ITS-G5.

Because of the competition between ITS-G5 and C-V2X, many papers compare the two technologies' performance. Sometimes in favor of one, while others prefer the other technology. Additionally, many sources only use simulations to evaluate the performance. Therefore, another goal of this thesis is to find out more about the real-life performance of V2X.

Finally, many Europe-wide projects are testing ITS-G5 in the field. These projects test a wide variety of parameters on V2X-enabled devices on real roads. The final objective is to log the information sent by these devices and evaluate the data.

1.2 Outline

Chapter 2 starts with the definition of central research questions. Chapter 3 then continues with a description of the idea behind V2X, the general use-cases, and the most important V2X messages. Subsequently, the background of the two V2X technologies are explained. Chapter 4 shows the preparation of the hardware needed for gathering ITS-G5 data and the software developed for the project. Lastly, the location and goals of six test campaigns are outlined. In Chapter 5 the data of the test drives is analyzed and presented. Chapter 6 discusses the collected measurement data and described the data described in the previous chapter. Lastly, Chapter 7 closes the thesis with a summary and an outlook for future works.

2 Problem Formulation

In the last years, more and more research projects evaluated V2X functionality and Europe's ITS-G5 technology. The EU project C-Roads[1] alone covers 100.000 km of roads with services involving ITS-G5. Additionally, VW rolled out the first V2X-capable mass-produced car in 2019. Now it would be important to not only simulate ITS-G5 vehicles but to measure real-world performance and collect data about real-world deployed Road Side Units (RSUs).

Therefore three main objectives have been defined and are evaluated in this thesis: (i) what is the actual rollout status of ITS-G5, (ii) how do practical applications differ from theoretical specifications, and (iii) what is the real-life performance of ITS-G5?.

Actual Roll Out Status of ITS-G5 The ITS-G5 standard already looks back on ten years of experience, with its standardization in 2010 [1]. Recently, in December 2019, the first mass-produced car equipped with ITS-G5 was launched. How well has the technology been adopted since then? What is the actual roll out status to date?

Difference Between Practical Application and Specification Theoretical specifications and practical applications usually differ at least a little. How much room for interpretation does the ETSI standard leave? Are there even parameters of the actual applications that violate the standard?

Real World Performance of ITS-G5 Many different publications are evaluating the performance of ITS-G5. However, many of them are calculations and simulations, with a broad gap in-between the estimations. For example, [2] shows in a simulation that to receive every packet from a moving node, the distance to the sender should be smaller than 138 meters. Anwar et al. [3] show a packet receive rate for 100-byte packets of zero after 500 meters. Contrary to that [4] shows that a transmission range of 700 meters should be achievable. Teixeira et al. [5] shows a drastic drop of the bitrate between 300 and 400 meters.

With all this different information, this work's essential questions are: What is the real-world performance of ITS-G5? How does the real-world data differ from the results discussed above?

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[1] `https://www.c-roads.eu/platform.html` accessed 19.03.2021

3 V2X Communication

In this chapter, V2X communication will be discussed. First, the general architecture, applications, and messages will be reviewed in Chapter 3.1. Afterwards the two competing Radio Access Technologies (RATs) are analysed: (i) the wifi derived standard 802.11p, in Europe known as ITS-G5[1] in Chapter 3.2, and (ii) the mobile network derived standard Cellular Vehicle to Everything (C-V2X) in Chapter 3.3.

3.1 General

Cars are being equipped with more and more sensors to be able to perceive their surroundings better and better. V2X was developed to share this environmental information with other road users. In general, V2X describes all forms of communication between a vehicle and any end point such as the infrastructure or another vehicle [6]. This communication architecture with the four most important communication nodes is shown in Figure 3.1.

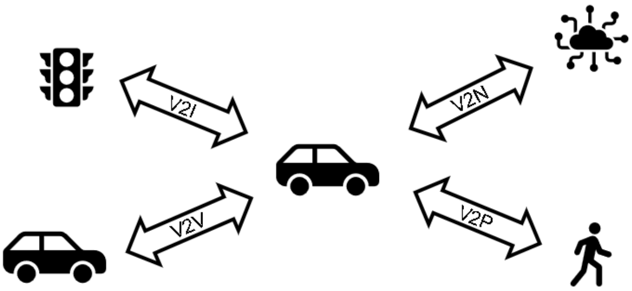

Figure 3.1: V2X communication [7] [8]

Using Vehicle to Infrastructure (V2I), the car should gain the possibility to communicate with road-infrastructure like traffic lights in order to get information, such as: the current colour, or the seconds until it will be turning green again [9]. Other connected infrastructure are traffic signs in order to communicate speed limits, construction sites or the risk of congestion on highways.

Vehicle to Vehicle (V2V) is the communication link between vehicles [9]. They can broadcast their position and inform each other about traffic conditions.

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[1] Intelligent Transport Systems - 5.9 GHz Vehicular Ad Hoc Network Physical Layer (ITS-G5)

Vehicle to Network (V2N) enables cars to get information from the internet, like traffic updates or infotainment data [10].

Lastly, Vehicle to Pedestrian (V2P) can be used to get information about pedestrians (or other vulnerable road users) in order to prevent accidents [11].

3.1.1 V2X Applications

In order to utilize the full potential of V2X, a wide variety of applications and requirements have been defined.

To get a good overview in this thesis, the applications have been grouped like in [9]. The only adjustment made is that infotainment was added to the list.

3.1.1.1 Road Safety

The applications most often associated with V2X are road safety use cases. These V2X use cases have been defined in order to prevent road fatalities, reduce harm when accidents are inevitable and lessen material damage.

Potential use cases in the road safety category, such as collision risk warning, stationary vehicle warning, vulnerable road user, roadworks warning and hazardous location are mentioned in [9]. Depending on the application, the minimum frequency of the message broadcast and the maximum tolerable latency varies. For instance, a pre-crash sensing warning is very time-critical since human reaction time needs to be taken into account. Here, the minimum frequency is 10 Hz, and the latency needs to be less than 50 ms [9]. Depending on the type of warning, one can generalize that latency of tens of milliseconds are needed in order to deploy road safety applications successfully [12].

3.1.1.2 Traffic Efficiency Management

Many different applications are covered by traffic efficiency management. It describes a variety of applications that all have the goal to make traffic more efficient by preventing traffic jams, minimizing waiting times at traffic lights and optimizing routes according to current traffic.

Some examples for traffic efficiency management, according to [9], are traffic light optimal speed advisory, intersection management and co-operative adaptive cruise control. Compared to road safety, traffic efficiency management is less time-critical and have a latency between 100 and 500 ms and a frequency between 1 and 10 Hz [9].

3.1.1.3 Infotainment

Infotainment or comfort applications provide data that enhance the driving experience, but ,contrary to traffic efficiency management, do not influence the roads chosen [12]. Infotainment can be media download, streaming of music and videos, or maybe online games for co-drivers.

In comparison to the applications mentioned before, low latency is not very important for comfort applications; however, the amount of data that needs to be downloaded is higher [12]. In [9] several applications are described that allow cars to access the internet over RSUs.

3.1.2 V2X Messages

In order to provide data for the implementation of the applications described in Chapter 3.1.1, a variety of messages have been defined. However, these messages have been regionally standardized and therefore differ from country to country. In the US, they have been mostly defined by Society of Automotive Engineers (SAE). In Europe, ETSI is in charge of defining V2X messages. This thesis focuses on the European implementations.

3.1.2.1 CAM

According to [13], the Cooperative Awareness Message (CAM) is the central piece of the ETSI protocol suite. The ETSI standard [14] specifies that the CAM informs other road users about the vehicle's position, driving direction, vehicle type (e.g. passenger car, motorcycle, truck, ...) and should be used for road safety and traffic efficiency management applications.

A CAM should be sent with a rate of 1 to 10 Hz, where 1 Hz is the default value [14]. Besides, the standard also states that CAMs are sent as broadcasts and are single hop, which means they are not forwarded by other vehicles. It is important to know that the default rate of 1 Hz is problematic and allows for inaccurate data when driving with higher speeds, as mentioned by [15]. The CAM transmission frequency can also be influenced by the Decentralized Congestion Control (DCC), which is described in Chapter 3.2.8.

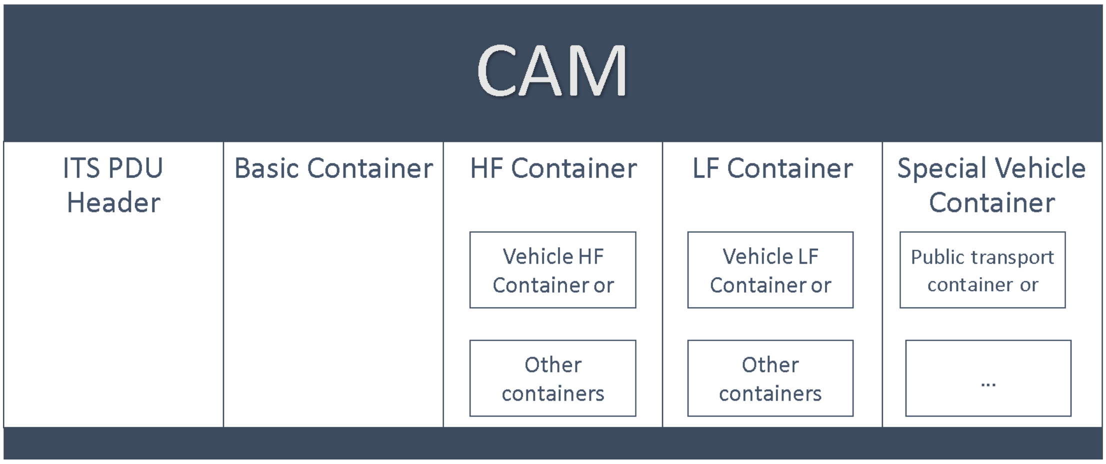

Figure 3.2: Structure of the Cooperative Awareness Message (CAM) [14]

The general structure of a CAM is shown in Figure 3.2. The ITS Protocol Data Unit (PDU) Header provides very general information like the protocol version and the message identifier (ID) as defined in [14]. The basic container includes information about the vehicle type and the position and is mandatory [14]. The standard [14] defines, that the High Frequency (HF) container consists of fast-changing data like heading, and is also mandatory. The Low Frequency (LF) container, on the other hand, is optional and contains static and slow-changing information like headlights information. Lastly, the standard states that vehicles with special roles shall make use of the Special Vehicle Container and provide further information.

The US-american pendant to CAM is the Basic Safety Message (BSM) [15].

3.1.2.2 DENM

Decentralised Environmental Notification Messages (DENMs) are event-driven messages to inform, for instance, about a collision, road works or weather conditions [16]. The ETSI standard defines that DENMs can be forwarded as long as the illustrated event is still ongoing. Message termination can happen for two reasons: (i) a pre-defined timer expires and (ii) a termination message is sent [16].

In order to keep messages about the event as up to date as possible, four types have been defined that allow altering the event message [16]:

1. New DENM: the original DENM sent by a vehicle describing the event.
2. Update DENM: is used to update event information and must be sent by the originated sender.
3. Cancellation DENM: informs about the event termination and must be sent by the originated sender.
4. Negotiation DENM: works like the cancellation DENM but is sent by another vehicle.

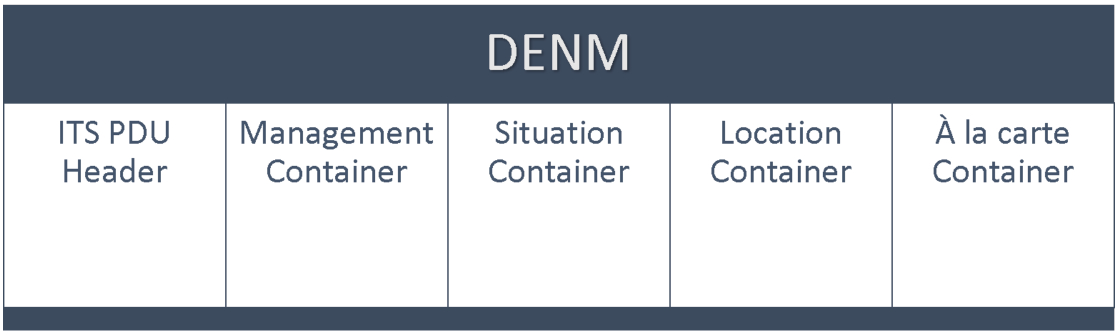

Figure 3.3: Structure of the Decentralized Environmental Notification Message (DENM) [16]

Figure 3.3 depicts the structure of a DENM message. Similar to the CAM, the ITS PDU Header of the DENM provides general information like protocol version and message ID. The management container includes all information needed for the management of the event, like detection time and event position [16]. The standard [16] defines that the situation container gives further information about the event, such as the information quality and a cause code which describes the kind of event that happened. ETSI states that the location container includes further location information and the road type. Lastly, the à la carte container provides space for any further information and is optional [16].

3.1.2.3 IVIM

In Vehicle Information Message (IVIM) is originally standardized in CEN ISO/TS 1932 [17]. In addition to the message the ETSI standard [18] also defines a facility layer protocol and requirements. IVIMs are used to communicate the content of static and dynamic road signs, such as (temporary) speed limits and road works warnings[18].

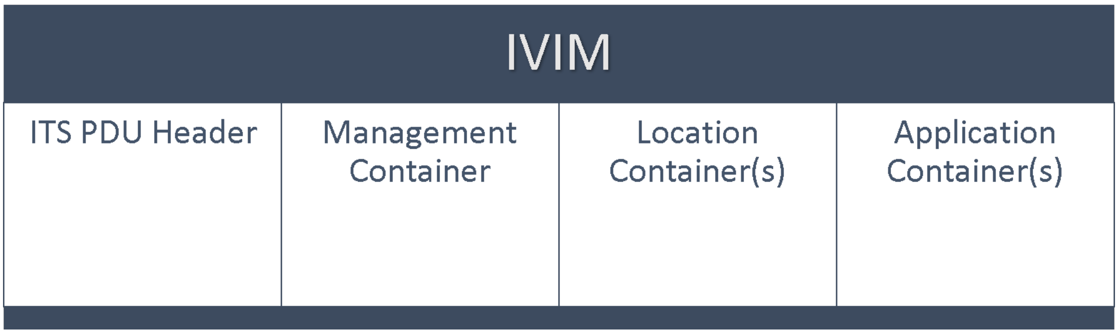

Figure 3.4: Structure of the Infrastructure to Vehicle Information Message (IVIM) [18]

The structure of the IVIM can be seen in figure 3.4. Apart from the ITS PDU header, the message consists of three containers: (i) the management container that contains general information about the IVIM in order for vehicles to decide if they want to further process the message, (ii) the location container that informs about the zones where the IVIM is valid, and (iii) the application container that adds additional information as well as the spacial validity [18] [17]. There can be one or more of each location and application container [18] .

3.1.2.4 Intersection Protocols

Intersections are often particularly dangerous because lane routing is not always intuitive, intersections can be confusing and sometimes vehicles have to yield despite green traffic lights. Therefore 4 protocols have been standardized originally by SAE [19] and the

International Organization for Standardization (ISO) [20] with a focus on intersection safety: Signal Phase and Timing (SPaT), Map Data (MAP), Signal Status Message (SSM) and Signal Request Message (SRM). ETSI also included those 4 protocols in their protocol suite [21]. Since ETSI added the ITS PDU headers to the message, they are called Signal Phase and Timing Extended Message (SPaTEM), Map Data Extended Message (MAPEM), Signal Status Extended Message (SSEM) and Signal Request Extended Message (SREM) in the ETSI architecture [21].

Map Data (MAP) MAP describes the topology of the intersection: the width of the road, the direction of each lane, connecting lanes, what kind of vehicles may use the lane and also what signal group the lane belongs to [19][20]. Of course the information provided by MAP only makes sense if the vehicle has accurate and up-to-date geographical data of the intersection.

Signal Phase and Timing (SPaT) SPaT includes information about the state of the traffic light and at least the time until the current state will change [19][20]. This is done by defining a Movement State container for every signal group.

Signal Request Message (SRM) and Signal Status Message (SSM): SRM allowes vehicles to request a signal change and the answer of the ITS station is then sent using a SSM, this enables the prioritization of traffic (e.g. public transport or ambulances) [19].

3.2 ETSI C-ITS

In order to enable V2X communication, ETSI standardized the ETSI Cooperative Intelligent Transport Systems (C-ITS) architecture in [8]. It builds upon the RAT ITS-G5, which makes some very minor changes to the original Institute of Electrical and Electronics Engineers (IEEE) 802.11p RAT standard [22]. The full protocol stack can be seen in Figure 3.5.

The hardware system architecture of ETSI C-ITS can be seen in Figure 3.6. ITS-G5 capable network devices are usually called Intelligent Transport System - Station (ITS-S). Figure 3.6 shows the two most frequently used ITS-S: a RSU and an On Board Unit (OBU).

RSUs are fixed ITS-S that are usually attached to the road infrastructure. They inform, among others, about road signs, construction works or speed limits using the ITS-G5. They can be connected to a central traffic server, where they are controlled. As mentioned in Section 3.1.1, RSUs might also be used for infotainment services and connect vehicles to the internet. An OBU must be equipped with at least one ITS-G5 capable network device, but can also use other network technologies. In addition to the ETSI C-ITS protocol stack, there must also be an interface to the car's sensors as well as an HMI interface to inform the driver can additionally be included.

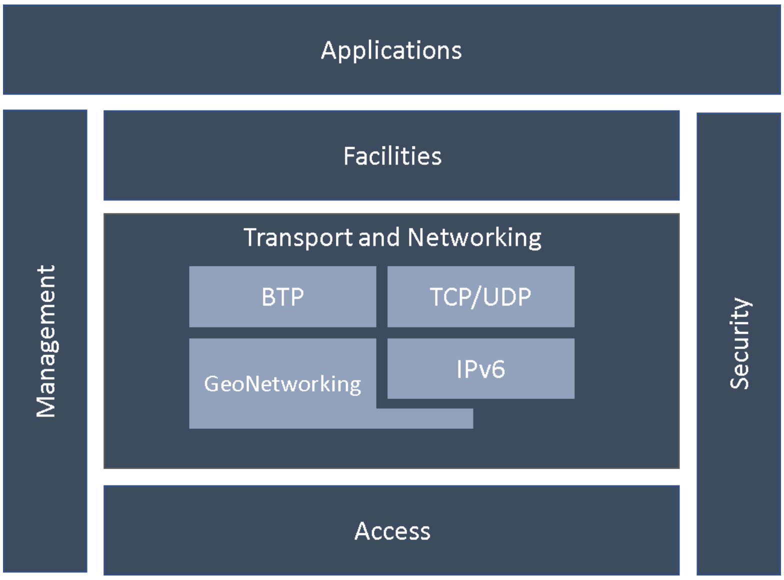

Figure 3.5: ETSI ITS architecture [8]

The following chapters will first introduce IEEE 802.11p and its implementations in Europe, the USA and Japan in Chapter 3.2.1. Later the layers of the ETSI C-ITS will be explained starting at Chapter 3.2.2 about the access layer. Chapter 3.2.3 describes the networking and transport layer, Chapter 3.2.5 the application layer, Chapter 3.2.6 the management entity and Chapter 3.2.7 the security entity. Lastly Chapter 3.2.8 describes the congestion control of ETSI ITS.

3.2.1 Origin: IEEE 802.11p

IEEE 802.11 [23] was first introduced in 1990 as a multipurpose WiFi standard. It already included multiple options for various physical layer such as infrared. However, 802.11 has two major drawbacks that made the development of 802.11p necessary in order to enable V2X communication: The connection setup takes a lot of time, and each station can only be part of one Basic Service Set (BSS) at any given time [24].

Therefore, the WiFi standard was finally extended in 2010 by 802.11p. The amendment allows communication in the allocated 5.9GHz band in 10 MHz channels [22]. The Orthogonal Frequency-Division Multiplexing (OFDM) layer specification was adapted from 802.11a. However, 802.11p uses a half-clock variant, and the channel size is halved (from 20 MHz to 10 MHz) [22]. Additionally 802.11p introduced Outside the Context of a BSS (OCB) Mode that allows communication without authentication, association, or data confidentiality services. This means communication is possible without being part of a BSS. Therefore, OCB Mode enables ad-hoc communication [22].

Table 3.1 shows the implementation of 802.11p in Europe, USA and Japan. The European and American implementations are very similar. In Japan, only a single channel

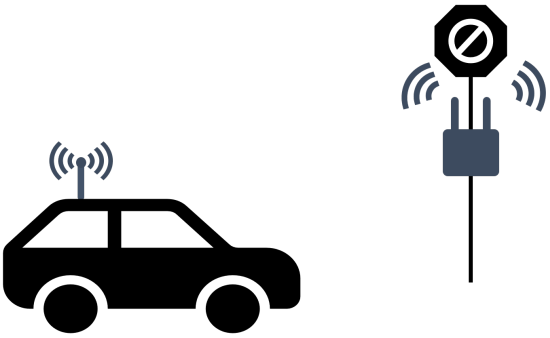

Figure 3.6: System architecture of ETSI ITS [8]

	Europe [25]	USA [26]	Japan [27]
RAT standard	ITS-G5	IEEE 802.11p	ARIB STD-T109
Frequency range	5.855 GHz-5.925 GHz	5.850-5.925 GHz	755–765 MHz
Number of channels	7	7	1
Modulation	OFDM	OFDM	OFDM
Upper layer protocol(s)	ETSI C-ITS	WAVE (IEEE 1609)	ARIB STD-T109, ITS Forum RC-013

Table 3.1: Adaptions of IEEE 802.11p in Europe, USA and Japan

in the 700 MHz band has been reserved for C-ITS applications.

3.2.2 Access Layer

The access layer of ITS-G5 consists of two Open Systems Interconnection model (OSI) model layers: a physical layer and a data link layer [25].

3.2.2.1 Physical Layer

As defined in IEEE 802.11p the ITS-G5 physical layer uses 10 MHz channels, the half-clock variant and OFDM. Different modulation schemes can be implemented, producing a transfer rate around 3 to 27 Mb/s [25]. Additionally, OCB Mode needs to be enabled.

Seven channels are available for C-ITS applications [22]. These have been grouped according to the type of application intended to use the frequency band. The ITS-G5A channels are reserved for road safety applications and may only be used by ITS-G5 stations [28]. ITS-G5B channels are reserved for non-safety relevant applications (e.g. traffic efficiency) [28]. Additionally, the standard [28] defines the two channels in ITS-G5D are reserved for future applications. This can be seen in Table 3.2. When looking at the naming of the C-ITS frequency band, ITS-G5C seems to be missing. However, the name was previously used for Radio Local Area Network (RLAN) that also enables ad-hoc communication [29].

ITS frequency band	Frequency range	Number of channels	Application
ITS-G5A	5875-5905 MHz	3	ITS road safety
ITS-G5B	5855-5875 MHz	2	ITS non safety
ITS-G5D	5905-5925 MHz	2	future ITS applications

Table 3.2: ITS frequencies in Europe. [22][28][25]

3.2.2.2 Data Link Layer

The data link layer consists of Logical Link Control (LLC) and Media Access Control (MAC) [25]. While LLC is responsible for distinguishing network level protocols, MAC schedules transmissions and deploys the access layer part of the DCC. DCC will be discussed thoroughly in Chapter 3.2.8.

3.2.3 Network and Transport Layer

The tasks of the network and transport layer are routing the packets and packing the data into individual data units. These tasks are performed by GeoNetworking and the Basic Transport Protocol (BTP) at ETSI C-ITS. In addition, the protocol stack also enables IPv6 packets to be sent via GeoRouting [30].

GeoNetworking GeoNetworking enables two particularly important services: geographic addressing and geographic forwarding. Each node evaluates a received packet, and if it is not the destination, the packet is forwarded. A location table is also maintained by every node for this purpose. GeoNetworking supports different addressing types: GeoUnicast, GeoBroadcast and Topologically scoped broadcast. The latter sets restrictions such as a single hop restriction. Additionally, an algorithm is used that detects duplicated packets and does not forward them to avoid overloading the network.[31]

Basic Transport Service BTP is designed to be very lightweight and only provides unreliable transport like User Datagram Protocol (UDP), which means packets may arrive out of order, duplicated or not at all [32]. The main task of the BTP is multiplexing different messages from the facility layer (e.g. CAM, DENM) for the transmission over GeoNetworking [32].

3.2.4 Facility Layer

The facility layer is responsible for providing services to execute the messages described in Section 3.1.2. In addition, it makes an Information Support Facility available, which provides database management functions (e.g. to create a local dynamic map) [33]. The standard [33] also defines a Communication Support Facility, which takes care of session management, for example [33]. Finally, there is a Management Facility, which is responsible for communication with the management block [33].

An example for a service running in the facility layer is the Cooperative Awareness (CA) basic service. In general, its tasks are encoding and decoding of CAMs, CAM generation, management of the CAM transmission frequency, and handle information from received CAM messages [14].

3.2.5 Application Layer

The application layer provides the services for the use cases defined in Section 3.1.1 by using the ETSI C-ITS protocol stack [33].

3.2.6 Management Layer

The management entity is responsible for cross-layer exchange among different layers and tasks, which is, for instance, important for congestion control. The management entity supports, among others, an ITS service advertisement, which is responsible for ITS application management like updating software and error handling [8].

3.2.7 Security Layer

The Security entity provides security and privacy functions for the whole protocol stack. Examples include, firewall, authentication and authorisation, identity management, hardware security modules [8].

3.2.8 Decentralized Congestion Control (DCC)

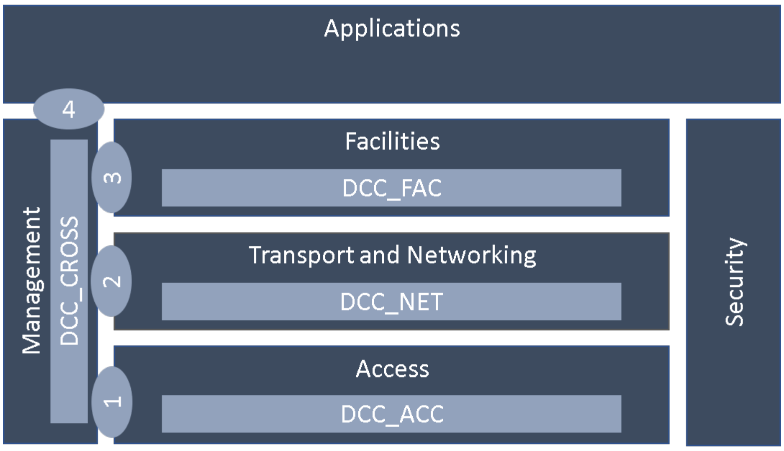

Figure 3.7: ETSI ITS architecture stack with DCC [34]

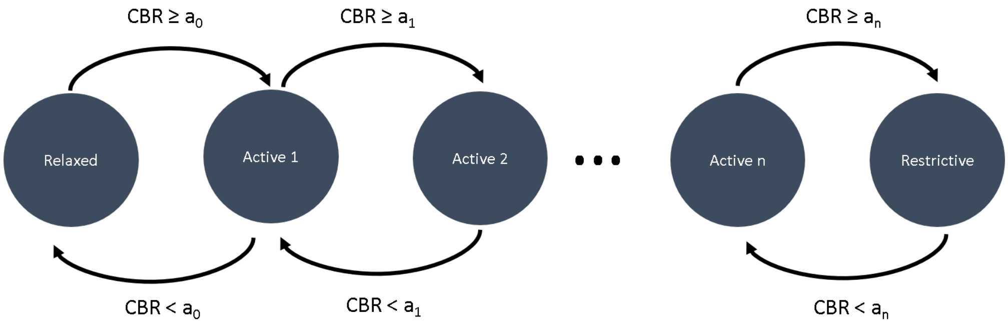

Figure 3.8: The reactive approach[35]

ETSI C-ITS deploys a cross-layer congestion control DCC, which is a mandatory part for all ITS-Ss. The goal of the DCC is to maintain network stability, throughput, and fair resource allocation. Furthermore, it should be possible to prioritize messages and the sending of messages should be based on the current channel load [34].

The DCC architecture can be seen in Figure 3.7. The DCC_CROSS entity is connected to the DCC entities of the different layers with interfaces, depicted as 1-4 in Figure 3.7. At the heart of the DCC architecture are the algorithms described in Chapter 3.2.8.1, which calculate parameters to keep the network load within well-defined limits. Chapter 3.2.8.2 then goes into the individual layers of the DCC architecture and explains which parameters are used and how.

3.2.8.1 DCC Algorithms

ETSI TS 102 687 [35] defines three parameters that can be used to control the network load:

- Transmit Power Control (TPC): If the network load is high, transmission power can be reduced. This leads to a shorter transmission range of the ITS-S, which means that the channel is free for farther away stations.
- Transmit Rate Control (TRC): When the load is high, the time between two consecutive packets (called T_{off}) can be increased.
- Transmit Datarate Control (TDC): A higher data rate can also be used to reduce T_{on} time of a station.

The ETSI standard [35] defines two approaches to adjust the three parameters above in order to reduce channel load:

Reactive Approach For the reactive approach different states are defined that go from ”Relaxed” (light load) to ”Restrictive” (overload), with n active states in between. For every state, one or a mix of the three parameters from above are defined. The state transitions are defined using Channel Busy Ratio (CBR) values. The state machine for the reactive algorithm can be seen in Figure 3.8. a_0 to a_n are values for the CBR, these state transitions are defined in [35] and [36].

Adaptive Approach The adaptive approach does not only take the current CBR values as input, but also past calculations. The adaptive approach in [35] calculates a value δ that describes the maximum fraction of time an ITS-S is allowed to use the channel. The value of δ depends on the current CBR, a past δ, and constants defined in [35]. The upper bound of δ is defined with 3%, and the lower bound is 0.06%.

3.2.8.2 DCC Architecture

The DCC architecture spans over most layers of the ETSI C-ITS stack. As depicted in Figure 3.7, the entities of the DCC architecture are called: DCC_ACC, DCC_NET, DCC_FAC and DCC_CROSS.

According to [34] the tasks of the **DCC_ACC** entity are

- The calculation of the CBR from the Channel Load (CL).
- The prioritization of messages to be sent according to their Traffic Class (TC).
- Temporarily storing of messages that cannot be sent right now in DCC queues. If their lifetime expires during the waiting time, the messages are deleted and the originating layer is notified of the dropping of the message via DCC_CROSS.
- Sending the message using the power control parameters and flow control parameters provided by DCC_CROSS.

The **DCC_NET** entity, as defined in [34], stores global DCC parameters received from other ITS-S. Furthermore, local DCC parameters are distributed to other ITS_S by including them in the GeoNetworking header. Finally, the GeoNetworking Forwarding Algorithm receives the required DCC parameters.

In **DCC_FAC** the network load generated by CAMs and DENMs is controlled. In addition, the message priority is written to the TC field [34].

The **DCC_CROSS** layer performs various calculations and passes this information to the DCC entities of the layers. For DCC_ACCESS the power control parameter and the flow control parameter is calculated with one of the algorithms described in Chapter 3.2.8.1. The DCC_NET layer receives the available resources and for DCC_FAC a channel resource limit for registered applications is calculated and communicated [34].

3.3 C-V2X

In contrast to the WiFi offshoot 802.11p, another RAT has now emerged: C-V2X. C-V2X is based on cellular technology and has the advantage of being able to connect directly to the internet using the existing wide-spread cellular infrastructure [37]. This means that not only V2N can be established directly, without a RSU as middle man. Also infrastructure V2X stations (V2I) could be superfluous, because vehicles could potentially get that information over the internet. In addition the network could be used to communicate with vehicles further away.

C-V2X is developed by the 3rd Generation Partnership Project (3GPP), which consists of seven standardization organizations that develop mobile communication protocols; ETSI is also part of 3GPP [2].

3.3.1 Communication Interfaces

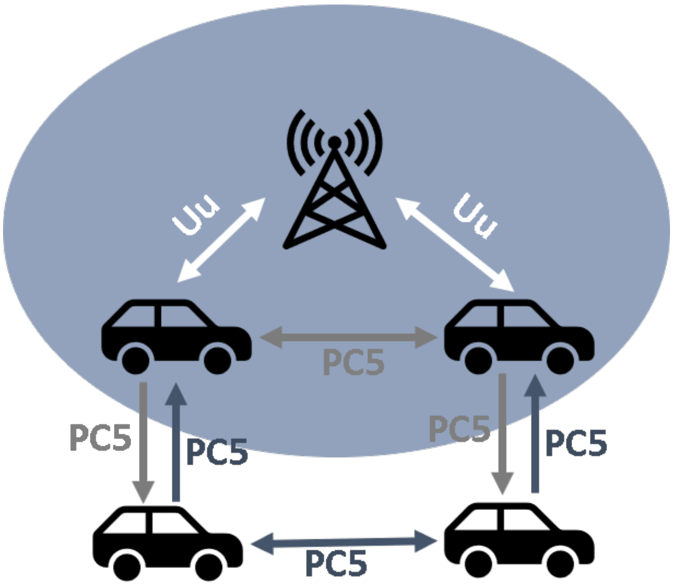

Figure 3.9: C-V2X communication interfaces [37] [38]

In general, V2X communication is enabled by User Equipment (UE), which describes any device that enables an end-user to communicate using LTE services [12]. C-V2X uses two LTE radio interfaces for V2X communication: the cellular interface called Uu and the Proximity-based Communication 5 (PC5) interface for direct communication, based on LTE Sidelink [39]. These two different communication paths are shown in 3.9.

Sidelink was first introduced in 3GPP Release 12 [40] under the name Device-to-Device

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[2] `https://www.etsi.org/committee/3gpp`

(D2D) as part of the Proximity Services (ProSe) and was intended for public safety use cases. D2D includes two modes: Mode 1 and Mode 2. In order to support V2X safety use cases and enable vehicular communication at high speeds, both have been revised and the V2X versions are called Mode 3 and Mode 4 [39] [41].

For PC5 Mode 3 the radio resources are allocated via the base station. The scheduling of the UEs works by means of control messages via the Uu interface [42]. Therefore Mode 3 only works when the UE is in coverage of a base station. The advantage of Mode 3 is that it allows for very efficient usage of sub-channel utilization.

In Mode 4 the UE is not in network coverage and manages the parameters of the radio resource autonomously. The UE chooses the parameters from pre-defined, zone-dependent resource pools according to its position, since the parameters can have regional differences. If no positioning is possible, the UE must not initiate V2X communication [42]. Mode 4 is therefore most similar to the communication in 802.11p.

In Figure 3.9, Mode 3 is shown with gray arrows and Mode 4 with blue arrows. If one car is in-coverage of a base station and one is not, the communication could work as pictured. This case is not specified in [42].

The cellular interface Uu can be used for indirect communication. Using the LTE base-station V2X messages can be distributed to UE out of reach for direct communication [38].

3.3.2 Architecture

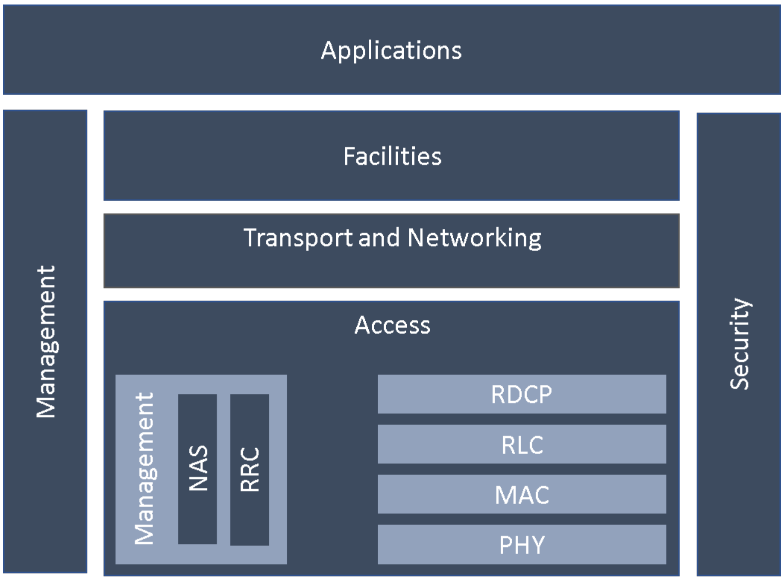

Figure 3.10: The ETSI ITS architecture using C-V2X for the access layer[43]

C-V2X Release 14 was standardized for the ETSI C-ITS architecture in 2020. The architecture is shown in Figure 3.10. The Aces Layer from Figure 3.5 has been replaced by an LTE Access Layer, but the remaining entities are, as far as possible, the same as in the ETSI C-ITS protocol stack (see Figure 3.5).

Access Layer The C-V2X physical layer uses frequency-division multiple access on its 10 and 20 MHz channels. The frequency bands used for this purpose are defined in Europe in the same way as for ITS-G5 (see Table 3.2) [43]. This means both technologies have to share the same frequencies. Two types of packets are used for C-V2X: Transport Block (TB) and Sidelink Control Information (SCI). While the TB contain the application data, the SCI (also called Scheduling Assignment) includes information about modulation, coding schemes, data length and resource reservation for semi-permanent scheduling. TBs are modulated with Quadrature Phase Shift Keying (QPSK) or 16 Quadrature Amplitude Modulation (QAM) and for SCI QPSK is always used [39]. For Sidelink Mode 3, the base station manages the resources and selects the sub-channels. In Mode 4 this is not possible. Pre-configured parameters are used instead [42]. There is also a congestion control implemented: CBR and Channel Occupancy Ratio (CR) are measured. If the CR is greater than a defined CR_{limit}, the UE must take steps to reduce it [44].

Other Layers The other access layer protocols for C-V2X in Figure 3.10 are from the LTE protocol stack and are defined in ETSI TS 136 300 [41].

3.4 Evolution

Both V2X standards have been extensively simulated and tested. Their weaknesses have been well researched and therefore two successors have been introduced. These are discussed in this chapter, first 802.11bd in Chapter 3.4.1 and then 5G New Radio (NR) C-V2X in Chapter 3.4.2. Lastly in Chapter 3.4.3 the regulatory steps taken by the USA and Europe are discussed.

3.4.1 802.11bd

Over the years, it has been shown that 802.11p has its weaknesses, especially with higher vehicle density, there can be larger delays in sending and receiving messages [45][46]. This could lead to safety critical messages not being delivered in time. Even congestion control only helps to a limited extent in this case.

Therefore, a task group was developed in 2019 to develop the successor 802.11bd. The goals for the new standard are to allow higher relative speeds of vehicles, double the range provided by 802.11p, co-existence with 802.11p, to be partially backwards compatible, and interoperability [47]. Since 802.11a was the base for 802.11p, its successor 802.11ac was chosen as the base for 802.11bd [47].

3.4.2 5G NR C-V2X

The new cellular vehicle-network standard 5G NR C-V2X is not intended to replace LTE C-V2X , but to extend and coexist in order to cover more use cases [47].

Among other things, the following goals have been set: both communication interfaces are to be improved, a mechanism to select the best possible RAT (there is now a choice between LTE Uu, LTE PC5, NR PC5 and NR Uu) and the co-existence of both standards. Since 5G NR C-V2X is not backwards compatible and LTE C-V2X is already deployed newer vehicle will need UEs from both versions [47].

3.4.3 Regulations

Until a November 2020, neither Europe nor the U.S. made a commitment between C-V2X and the respective 802.11p standard. Unlike China, which is pushing the development and deployment of C-V2X [48] [49].

This ambiguity means that the decision is highly contested. Different stakeholders hold different opinions and try to substantiate them with publications. This can be observed for example in [50], where a possible transmit distance of ITS-G5 of 400m is demonstrated with a Package Receive Ratio (PRR) of 90%, [3] shows a PRR of only 10% at 400 meters distance. According to [51] the PRR is 0% at this distance. [3] and [51] obtained their results in a simulation, while [50] uses real measured values.

In the meantime, however, the US has made a decision and opted for C-V2X. One half of the frequency band reserved for 802.11p will bee freed for WiFi, the other half will be dedicated for C-V2X applications [49]. The EU is also considering freeing further parts of the 5.9 GHz frequency band for WiFi, but this will probably not affect V2X [52]. In the EU, both C-V2X and ITS-G5 are allowed to use the 5.9 GHz frequency band, since the EU defines the spectrum usage in a technology neutral way [53].

4 Preparation

In this chapter the preparation done before the test drives will be discussed. First, the hardware used is described in Chapter 4.1, then the software to log and analyse received V2X messages is described in Chapter 4.2. Finally, in Chapter 4.3 the planned test drives and their goals are illustrated.

4.1 Hardware

For the test drives two ITS devices are needed: (i) a V2X sender, and (ii) a V2X receiver. The V2X sender should be a RSU that allows messages to be modified and sent. The other device will be used as part of the V2X monitor. Besides receiving and forwarding messages the Global Positioning System (GPS) module should also be usable on its own in order to get the position of the vehicle when receiving a message. The following pages contain a summary of the equipment that used in order to conduct the test drives described in Chapter 4.3.

Siemens ESCoS Roadside Unit It offers connectivity using WiFi, Bluetooth, GPS, 802.11p, LTE and Ethernet. Additionally it offers a service Graphic User Interface (GUI) that allows the user to modify V2X messages, monitor received messages, send messages, and change other RSU dependant settings [1]. The Siemens RSU is shown in Figure 4.1.

Cohda MK 5 The Cohda MK 5 was selected for the V2X Monitor. It is an OBU, can send and receive 802.11p, has a GPS receiver and runs Linux. It can be connected via Ethernet, Controller Area Network (CAN) or Universal Serial Bus (USB). The Cohda MK5 has some pre-installed programs, one of them is a monitor mode [2]. Cohda MK5 is shown in Figure 4.2.

Laptop A laptop running Ubuntu was used to form the V2X monitor together with the Cohda MK5. The laptop runs the ITS Communication Logger described in Chapter 4.2.1.

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[1] SIEMENS ESCoS Roadside Unit User Manual V1.1 (2019)

[2] Cohda MK5 “MK5 OBU.” Cohda Wireless, `https://cohdawireless.com/solutions/hardware/mk5-obu/` (Accessed 04.02.2021.)

Figure 4.1: The Siemens ESCoS Roadside Unit

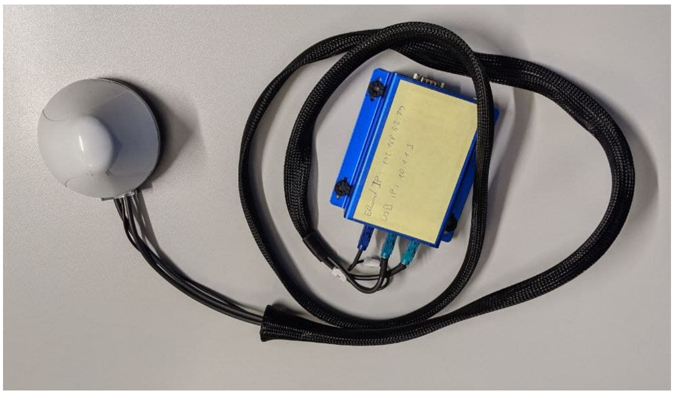

Figure 4.2: The Cohda MK5 with an antenna

Monitor Setup The monitor setup consisted of the Cohda MK5 and the laptop. These two devices were connected using Ethernet as shown in Figure 4.3. During test drives both devices were powered through the automobile auxiliary power outlet using an inverter. For best radio reception the Antenna was placed at the roof of the vehicle, as shown in Figure 4.4.

4.2 Software

4.2.1 C-ITS Communication Logger

fix image!

past tense here too?

The program flow of the ITS communication logger is shown in Figure 4.5. In the main function four threads are created, three are given a shared stop variable. One is set as a daemon thread, which means it will be killed when the main program exits. After the four threads are started, the main program sleeps until the user exits the program

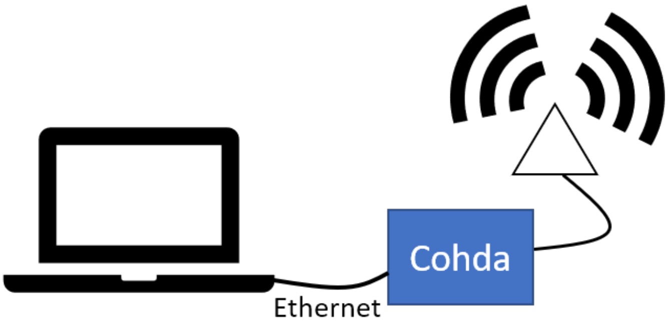

Figure 4.3: The Setup of the V2X Monitor

Figure 4.4: Car with Mounted Cohda Antenna on the Roof

using *CTRL + C*, which will raise a keyboard interrupt exception in the main program. Once the exception is caught the three stop variables are set the three threads are joined and the main program exits.

The four threads all have one job each. The *send_GPS_thread* connects to the Cohda module using Secure Shell (SSH) and gets information about the current position using the program gpspipe. Using the pipe command the output is directed to the netcat tool, which sends it to the laptop at port 41097 using UDP packets. Once the stop variable is set, the thread closes the ssh connection and returns.

The counterpart is the *receive_GPS_thread*, it binds port 41097, when empty GPS data is received an error message is displayed to the user. If the data is not empty it is written to a file including a timestamp.

The *send_monitor_thread* connects to the Cohda module using SSH, starts the monitor program and configures it to forward received 802.11p packets to the laptop. If the stop variable is set the thread closes the SSH connection and returns.

Lastly, the *receive_monitor_thread* starts tcpdump, a command line packet capture

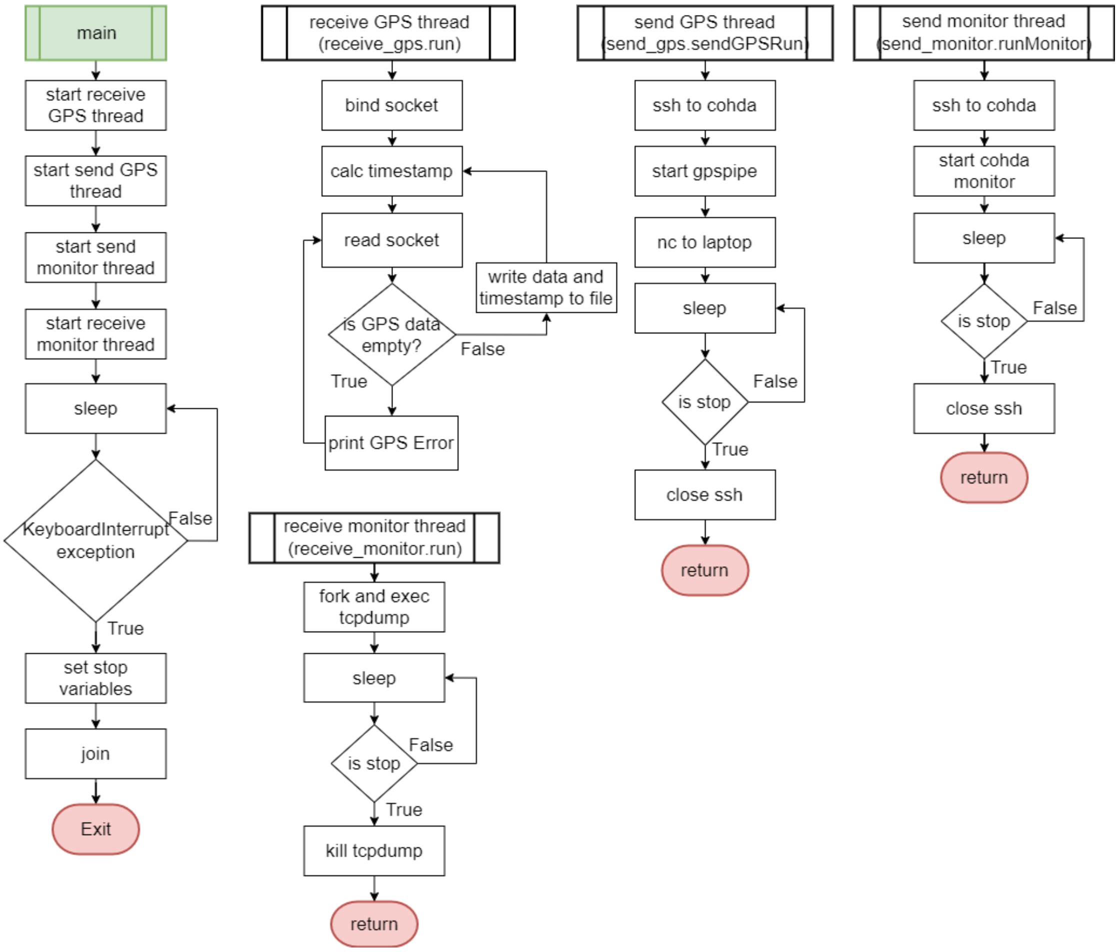

Figure 4.5: Program flow of the ITS Communication Logger

tool, and instructs it to save the data in a pcap file. When the stop variable is set, the thread kills tcpdump and returns.

4.2.2 C-ITS Communication Data Extraction Tool

This python programs takes the pcap file and the file containing the gps data created by the C-ITS Communication Logger as input. The programm creats a csv file containing the most important parameters for further data processing using Excel.

With the help of the Python library *pyshark* the data of the pcap files are extracted. Then the position of the car at the time of the arrival of the message is read from the gps file. Finally the following data are stored in the output file: timestamp, longitude and latitude of the car, ITS version, protocol, signal strength, speed of the car according to GPS, the station ID and the position of the sender.

4.3 Test Drives

A total of six test drives were planned. Three of them analyze test tracks from different projects. The other three test drives were planned with the Siemens RSU. In all cases the V2X monitor described before was used to record messages and the current position of the car.

4.3.1 Graz A2 Motorway

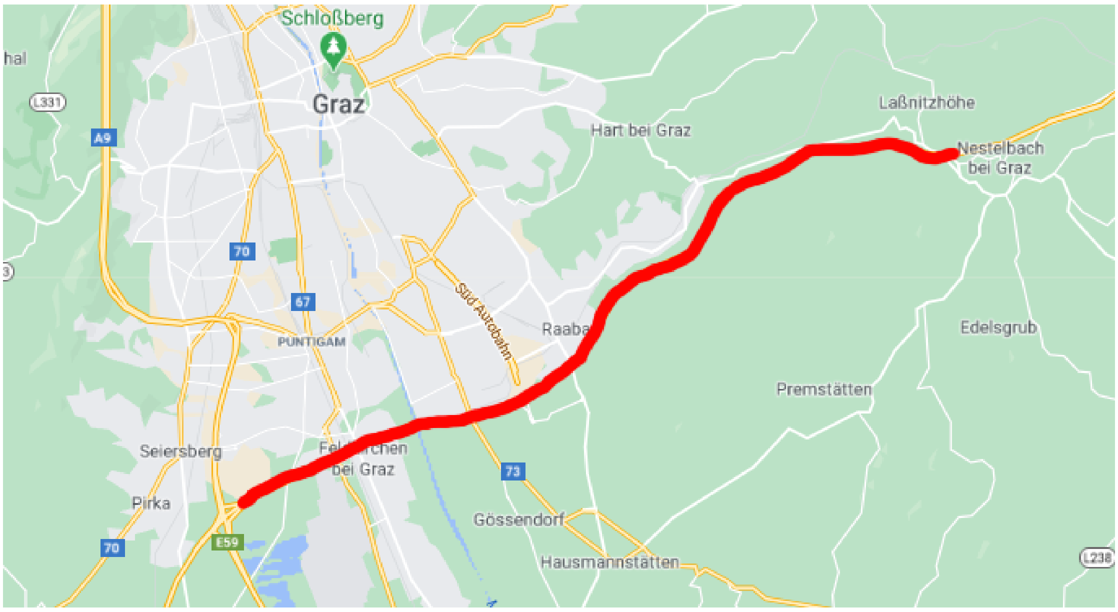

Figure 4.6: V2X stations at A2 motorway at Graz. Created with maps.gooogle.com.

12 RSUs were set up as part of C-Roads and ICT4CART by Asfinag. They are positioned at the A2 motorway between Laßnitzhöhe and Unterpremstätten, this route can be seen in Figure 4.6.

The specific goals for the test drive were: (i) to find out if the RSUs are turned on, (ii) to find out what they are sending and if this information is useful, (iii) to find out if the density of the different RSUs is high enough to achieve seamless network coverage, (iv) and finally, what is the maximum distance for reliable message transmission?

4.3.2 Vienna

In Vienna, Asfinag has set up several RSUs for C-Roads. A test section has been set up, along the freeway into the city (S1 from the Vössendorf junction, A4 and A23); it is marked in red in Figure 4.7. Along the Handelskai there are additional RSUs at traffic lights; these are marked in purple in Figure 4.7.

Figure 4.7: V2X stations at S1, A4 and A23 motorway and at Handelskai in Vienna

Since there are some shorter tunnels on the highway route, it would be interesting to see how they influence the reception of V2X messages. In addition, the RSUs at Handelskai should provide information about the intersections and traffic light status, here it is interesting whether this information is correct and which protocols are used.

4.3.3 Italy - South Tyrol

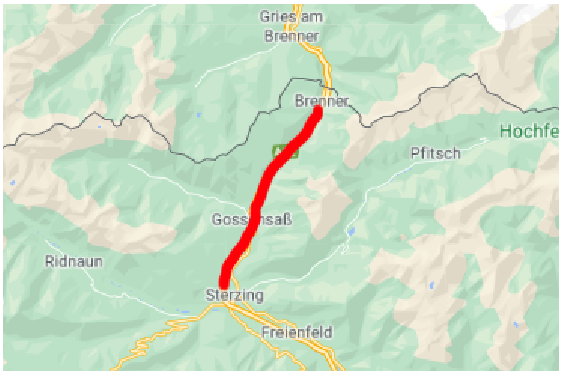

Figure 4.8: Route of the test drive in South Tyrol

In Italy, C-ITS stations were set up along the motorway Brennero by “Autostrade del Brennero” as part of C-Roads, ICT4CART and BrennerLEC. In this test drive, the section between Brennero and Sterzing was covered. The route can be seen in Figure 4.8.

Interesting for this test drive was if the Italian ITS-Ss differ from Austrian ITS-Ss and if so, how.

4.3.4 Distance Measurement Under Optimal Conditions

Figure 4.9: Overview of the distance measurement campaign

The primary objective of this test drive was to measure the possible distance a V2X message can be received over. For this purpose, an optimal test setup was chosen: a straight road with as little traffic as possible. The RSU was set up at the point marked with a red Point of Interest (POI) flag in Figure 4.9. Its power supply was esnured with a high capacity lead gel accumulator. The RSU was set to send a DENM message every 100 milliseconds. The route provides 800 meters of direct line of sight to the RSU, which is marked in green in Figure 4.9. Afterwards there is a corner with bushes for about 150m until the line of sight gets obstructed by buildings.

4.3.5 Distance Measurement in an Urban Environment

In the urban measurement, the RSU was placed at two different positions: first at the parking lot (red marker in Figure 4.10) and then at the roof of a three-story building (green marker in Figure 4.10). Afterwards, the immediate surroundings were scanned by driving around with a vehicle, in which the V2X monitor was installed.

The aim of this test drive was to find out the maximum reception range in an urban environment. It is also interesting to see how strongly the signal is shielded by buildings and whether interference from WiFi signals can be detected.

4.3.6 Test Drive of a V2X Equipped Car

The VW Golf 8 was launched in December 2019 and was the first mass-produced car to be equipped with 802.11p. The V2X feature is called Car2X by VW and is said to bring many features that provide more safety on the road. For example, a "stationary vehicle" warning is sent out when the car's alarm is on and the car has been stationary

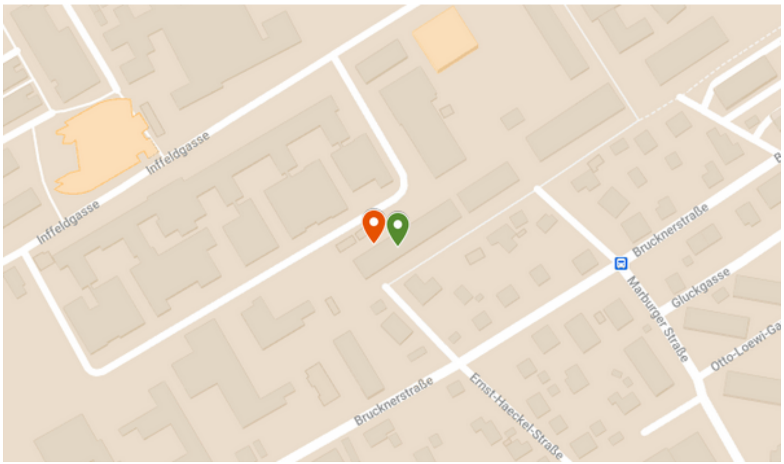

Figure 4.10: Two positions of the RSU during the test drive

for more than a minute, or a critical driving situation warning is sent out in the event of heavy braking [3] [4].

The aim of this test drive is to borrow and test a VW Golf 8 using the V2X monitor setup and the RSU. The main questionsare: Are the promised features really sent out and if so, what exactly do the messages say? And how does the car react to messages from the RSU?

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[3] `https://www.adac.de/rund-ums-fahrzeug/tests/assistenzsysteme/c2x-im-vw-golf-8/` visitied 02.02.2021 (German source)

[4] `https://www.heise.de/select/ct/2020/7/2002313225800012527` visited 02.02.2020 (German source)

5 Results

This chapter presents the results of the test drives described in Chapter 4.3.

For the evaluation of the test data, the csv files of the python tool were processed in Excel. For the calculation of the distance between two geographical points, the *Spherical Law of Cosines*[1] was used, since it can be programmed as a one-liner with Excel. The equation is shown in Equation 5.1. $lat1$ and $long1$ represent the coordinates of the vehicle and $lat2$ and $long2$ represent the coordinates of the RSU that send the message. R represents the mean radius of the Earth and was chosen to be 6371000 meters.

$$d = acos(sin(lat1)sin(lat2) + cos(lat1)cos(lat2)cos(long1 - long2))R \tag{5.1}$$

For the following results only messages were used that were received correctly. Messages that arrived in parts (i.e. were corrupted) were always discarded. However, sometimes this was difficult to detect because only a few bits were shifted or flipped. Those messages were sorted out as good as possible by hand. This entails, that messages with an ITS version other than 1 or 2 were deleted, since no other version exists. Messages with message IDs bigger than 13 were also discarded because message IDs have only been defined from 1 to 13. Messages with stationtypes not between 0 and 15 were also deleted. Lastly, messages with strange positions in the GeoNetworking Layer were deleted. This includes messages with negative coordinates and messages with latitudes and longitudes that should not occur in the specific test drives.

Lastly, to calculate the frequency of the transmitted CAMs of the RSUs, the average over the CAM frequencies of all received CAMs in a radius of 200 meters was chosen. This distance was chosen because [3] shows that even with unexpectedly high data rates, the packets should arrive at a high proportion.

5.1 Graz A2 Motorway

Before further processing received the messages were filtered out as described in Chapter 5. In addition messages where the RSU's latitudes were not between 46.9 and and 47.1 were deleted. Messages with RSU longitudes smaller than 15.3 and bigger than 15.6 were deleted.

In Figure 5.1, the positions of the transmitting RSUs were mapped with green POI markers. The red POI marker shows a V2X-enabled car detected in the C-ITS log. The detected car is transmitting CAMs at a frequency of 3.3 Hz. It is identifiable as a car

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[1] https://www.movable-type.co.uk/scripts/latlong.html

because *stationType* in the Basic Container is set to *passenger* car in the CAM. In the GeoNetworking layer it can be observed, that the position of the detected car changes.

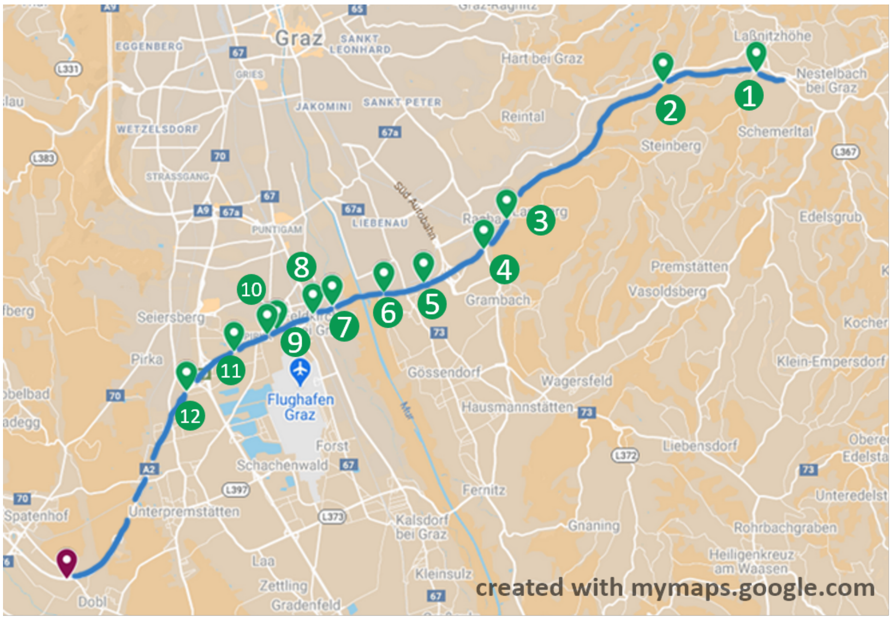


Figure 5.1: Position of the RSUs (green) and one V2X-capable car (purple) along the A2 near Graz [54]

In Table 5.1, details of the individual RSUs along the route can be found. f_{CAM} describes the average frequency of the received CAM messages, where the distance between the car and the RSU was smaller than 200 meters. The next column is the associated standard deviation. Sample size describes the number of CAM messages that were received in the defined 200 meter radius. Max range describes the maximum distance between RSU and test vehicle at which a message was received. MessageID specifies the parameter in the ITS PDU header that describes the protocol. Most RSUs send DENMs (1), CAMs (2) and IVIMs (6).

Noticeable is that the frequency of RSU 9 is only 0.64 Hz, however only 19 packets were received by that RSU and only 4 of those were CAMs.

It is also worth noting that all packets have a 1609.2 Secure Packet in the GeoNetowking protocol, as defined in [55].

At first glance, the received DENMs do not seem to make sense. Despite the sunny weather, a heavy rain warning was sent. The weather from the test drive can be seen in Figure 5.3. The weather warning is marked yellow in the Wireshark screenshot in Figure 5.4. Also warnings of stationary vehicles, and shed loads are constantly sent, these warnings could not be verified while driving and seem to be sent randomly. All warnings have informationQuality 2, this is recommended by [57] when only one automated source alerts to an event. Higher values must come from multiple sources and even validation of the information is demanded.

RSU	avg. f_{CAM} (Hz)	SD f_{CAM} (Hz)	sample size	max range (m)	messageID	version
1	1.00	0.07	13	608.6	1, 2, 6	2
2	1.00	0.00	17	852.0	1, 2	2
3	1.00	0.00	16	1794.5	1, 2, 6	2
4	1.01	0.00	17	1916.9	1, 2	2
5	0.99	0.02	16	1729.7	1, 2	2
6	1.00	0.02	17	1714.4	1, 2, 6	2
7	1.00	0.00	18	2020.6	1, 2, 6	2
8	1.00	0.01	18	1071.4	1, 2, 6	2
9	0.64	0.29	3	96.5	1, 2, 6	2
10	1.01	0.00	18	1743.4	1, 2, 6	2
11	1.00	0.00	18	1713.5	1, 2, 6	2
12	1.00	0.03	21	1013.4	1, 2	2

Table 5.1: Average CAM frequency and standard deviation, sample size, range, protocols and C-ITS versions sent per RSU in Graz

Figure 5.2: The achieved network coverage along the A2 near Graz. (Created with Excel 3D Map)

Figure 5.2 shows the "network coverage" of the RSUs. At each position of the test vehicle where a message from an RSU was received, a blue dot was drawn.

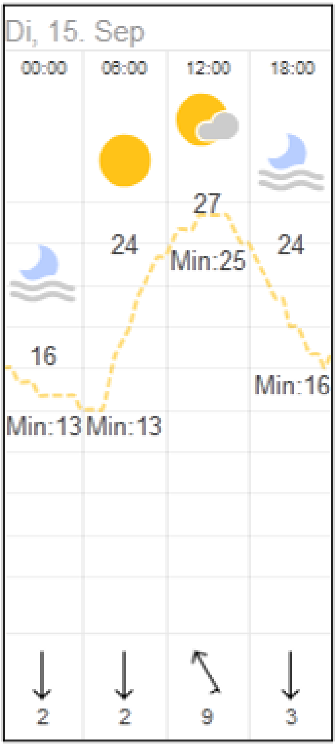
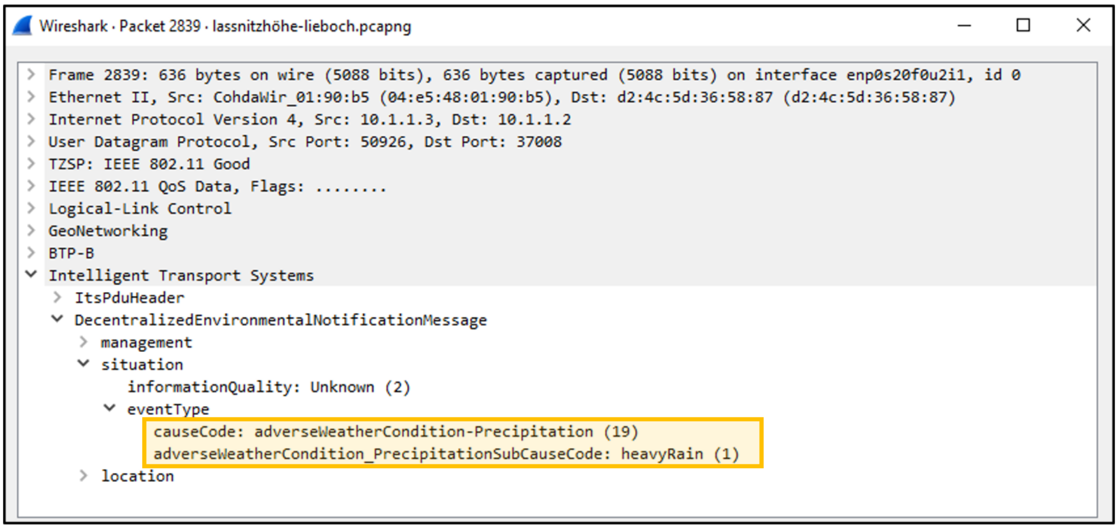


Figure 5.3: Screenshot of the weather on the day of the test drive [56]



```
> Frame 2839: 636 bytes on wire (5088 bits), 636 bytes captured (5088 bits) on interface enp0s20f0u2i1, id 0
> Ethernet II, Src: CohdaWir_01:90:b5 (04:e5:48:01:90:b5), Dst: d2:4c:5d:36:58:87 (d2:4c:5d:36:58:87)
> Internet Protocol Version 4, Src: 10.1.1.3, Dst: 10.1.1.2
> User Datagram Protocol, Src Port: 50926, Dst Port: 37008
> TZSP: IEEE 802.11 Good
> IEEE 802.11 QoS Data, Flags: ........
> Logical-Link Control
> GeoNetworking
> BTP-B
v Intelligent Transport Systems
  > ItsPduHeader
  v DecentralizedEnvironmentalNotificationMessage
    > management
    v situation
        informationQuality: Unknown (2)
      v eventType
          causeCode: adverseWeatherCondition-Precipitation (19)
          adverseWeatherCondition_PrecipitationSubCauseCode: heavyRain (1)
    > location
```

Figure 5.4: Screenshot from the DENM warning from heavy rain in Wireshark

5.2 Vienna

Figure 5.5: The RSU positions in Vienna (in blue) and on the motorway (in red) [58]

As described in Chapter 5 erroneous messages were filtered. Additionally messages where the received sender latitude was not between 48.10 and 48.3 were discarded. The received sender longitude was also restricted to values between 16.3 and 16.5. Figure 5.5 shows 18 RSUs from which data was received. RSUs in the city were marked with a blue POI marker, RSUs on the S1, A4 and A23 motorway were marked with a red POI marker. Additionally, two RSUs were encountered, which were marked with a yellow POI marker. Both were not analysed in detail since RSU a was not known to us when planning the route and RSU b sent only very limited messages. One RSU encountered in the city can be seen in Figure 5.7. Additionally, CAMs from passenger cars were received with seven different station ids during the test drive in Vienna, their positions can be seen in Figure 5.6.

Table 5.2 shows the corresponding data of the RSUs. f_{CAM} describes the frequency of the received CAMs, as in Chapter 5.1, only CAMs where the distance between RSU and receiver was less than 200 meters were included, the number of CAM that full fill this requirements can be found under sample size. The max range describes the maximum distance between RSU and receiver at which a message was received. The messageID describes the protocols that an RSU sends: DENM (1), CAM (2), SPaT (4), MAP (5), IVIM (6), SSEM (10). The protocol version describes the ITS protocol version used by the RSU and can be either 1 or 2.

Table 5.2 shows no average f_{cam} and standard deviation for RSUs 6 and 10 since no

Figure 5.6: Positions of encountered V2X capable cars in Vienna

RSU	**avg. f_{CAM} (Hz)**	**SD f_{CAM} (Hz)**	**sample size**	**max range (m)**	**messageID**	**version**
1	1.00	0.01	58	2256.5	1, 2, 4,5	2
2	1.00	0.01	56	1596.8	2,4,5	2
3	1.00	0.01	79	869.1	1, 2, 4, 5	2
4	1.00	0.02	36	1696.9	1, 2, 4, 5, 10	2
5	0.67	0.3	12	1484.3	1, 2	2
6			0	433	2	1
7	1.00	0.01	8	2300	1, 2	2
8	0.60	0.29	3	955.4	2	1
9	0.75	0.25	12	1660.4	1, 2	2
10			0	1167.7	2	1
11	0.67	0.33	4	1.059	2	1
12	1.00	0.01	13	785.5	1, 2	2
13			0	791.6	6	2
14	1.00	0.00	19	1240.1	1, 2	2
15	0.94	0.13	17	1257	1, 2	2
16	1.00	0.02	12	1548	1,2, 6	2

Table 5.2: Average CAM frequency and standard deviation, sample size, range, protocols and C-ITS versions sent per RSU in Vienna

[redacted]

Figure 5.7: Photo of an RSU mounted next to a traffic light at Handelskai and Chrastekgasse

messages were received in the 200m radius defined before. RSU 13 did not send out CAMs at all. Additionally RSU 6, 8, 10 and 11 used C-ITS version 1 as opposed to version 2.

Figure 5.8 shows visualized MAPEM data from RSU 1. In the figure incoming lanes have been colored orange and exiting lanes white, parking space has been marked yellow and crosswalks blue. The MAPEM maps every lane to a number and also specifies for incoming lanes which exiting lanes can be taken (marked with arrows in Figure 5.8) and to which signaling group of the SPaTEM the lane belongs to (which is indicated by the color of the arrow). Each lane is described by at least three points. All points are described by their distance from the reference point (marked with the red POI marker) in north and east direction. To express southern or western directions the corresponding values are negative.

In order to get information about V2X connectivity inside a tunnel the example pictured in Figure 5.9 was extracted from the data. The red POI marks the position of RSU 12. The blue square marks a 118 meter long underpass and the green square the Rannersdorf tunnel of 1880m. 29 messages from RSU 12 where received inside the Rannersdrof tunnel with a CAM frequency of 1. Since no GPS signal was received inside the tunnel, the position of the car when receiving the messages was not able to be recovered, due to the measurement setup having only GPS as positional input. Inside the blue underpass also a CAM frequency of 1 was received, which suggests that no message was lost.

Figure 5.10 shows the *network coverage* achieved on the motorway. Since the tasks of the RSUs in the city is to organize a single intersection each, it does not make sense

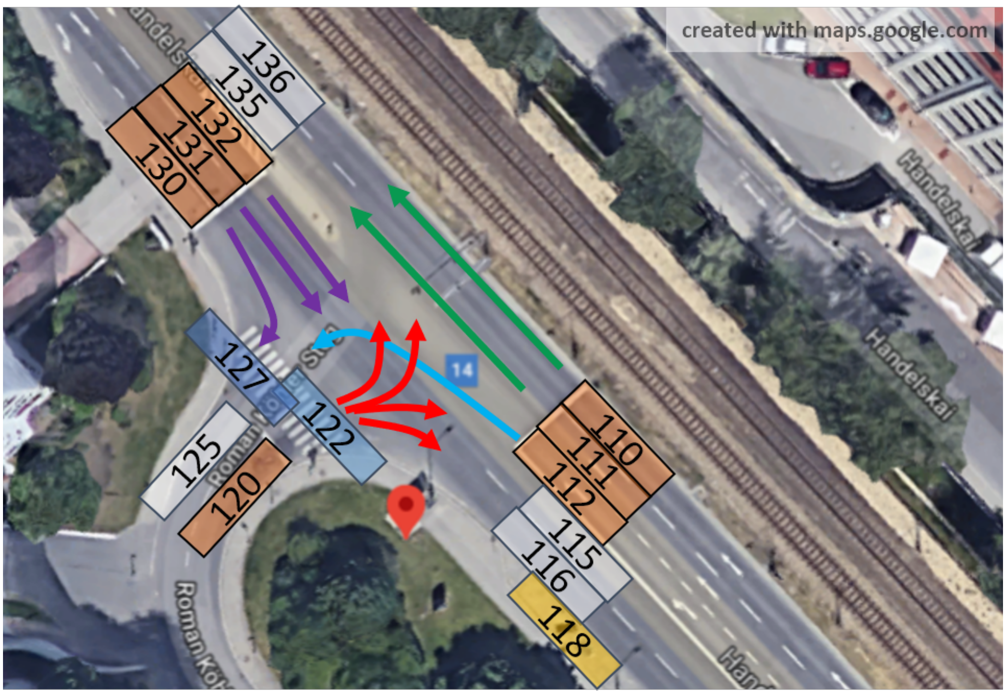


Figure 5.8: Visualized data from a MAPEM at Handelskai and Roman Köhler Steg in Vienna

Figure 5.9: RSU 12 with an underpass and the Rannersdorf tunnel in front

to show a *coverage* map. Also worth mentioning is that the coverage around RSU 11 looks off because only messages before the position of the RSU were received and not after. Notable is that the signal strength becomes strongest when the test vehicle is still more than 300 meters away from the RSU. It is possible that the location of the RSU is incorrectly entered in the GeoNetworking Layer or that the RSU antenna was shielded in one direction, but more data needs to be recorded to verify this assumption.

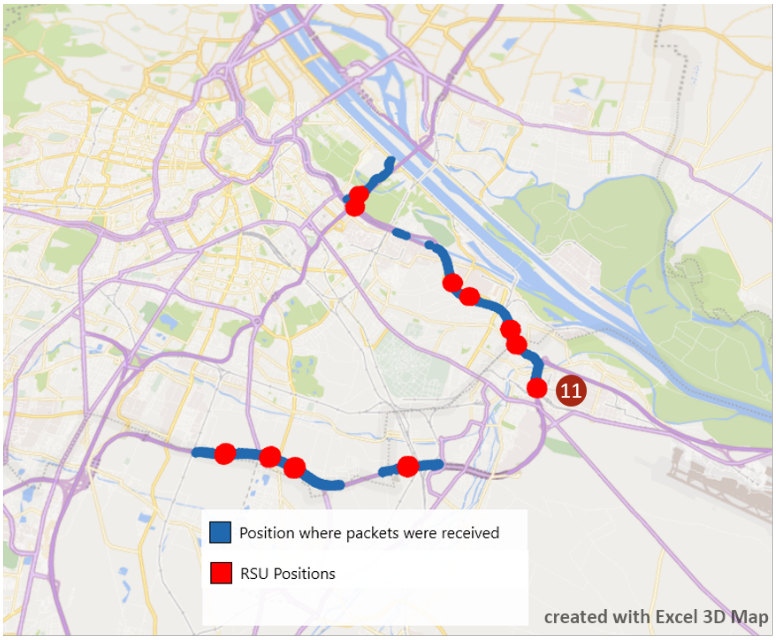


Figure 5.10: The achieved network coverage along the test track on the S1, A4 and A23 around Vienna

5.3 Italy

As described in Chapter 5 erroneous messages were discarded from the log files. Furthermore values for the received RSU latitude was restricted to fall between 46.80 and 47.01 degrees. Longitudes had to be greater than 11.41 and smaller than 11.51 degrees.

The map shown in Figure 5.11 shows the RSUs from which data was received. On the day of the test drive, data was received from 4 different RSUs. The positions of the RSUs were extracted from the source position container in the GeoNetworking layer.

Figure 5.12 shows the positions where messages were received from RSUs. It is notable that packages from RSU 1 dispaly two issues: The positions where messages were received from the RSU do not overlap with the position of the RSU and secondly 480 meters before reaching the position of the RSU no more packages are received. Messages from RSU 2 look very similar: no packages were received at the location of the RSU. The *reliable* package transmission stops 300 meters before the RSU's position, however a burst of 10 messages is received 40 meters before the RSU's location. Lastly, also the messages received from RSU 3 seem abnormal, compared to stations in Vienna and Graz. The CAM frequency is consistent at 1 Hz until 350m before the RSU position. After the RSU position a few more sporadic CAMs are received. However, the receiving of DENMs was never impaired.

Why RSU 1, 2 and 3 displayed the behaviour described is unknown. They could be mounted in a way, that the signal is reflected and shielded. However, these are only speculations and would need to be verified with further test drives.

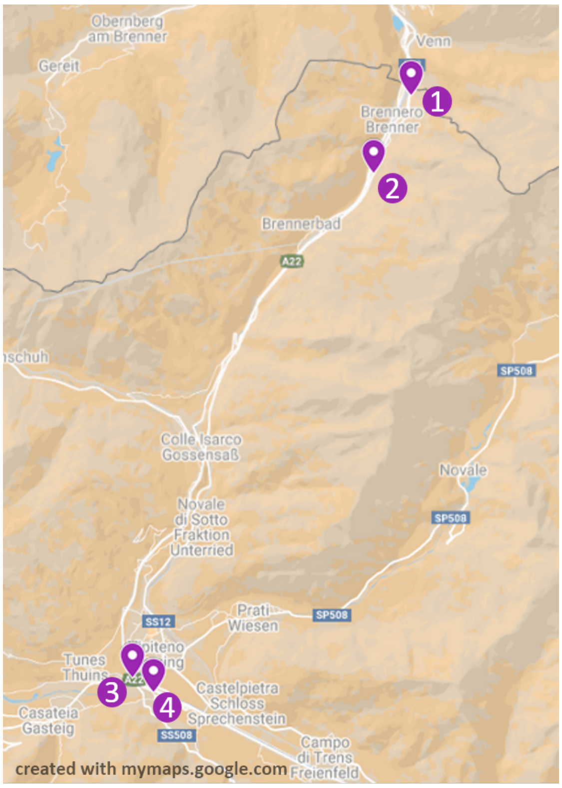


Figure 5.11: The RSU positions between the Brenner and Stierzing on the A22 [59]

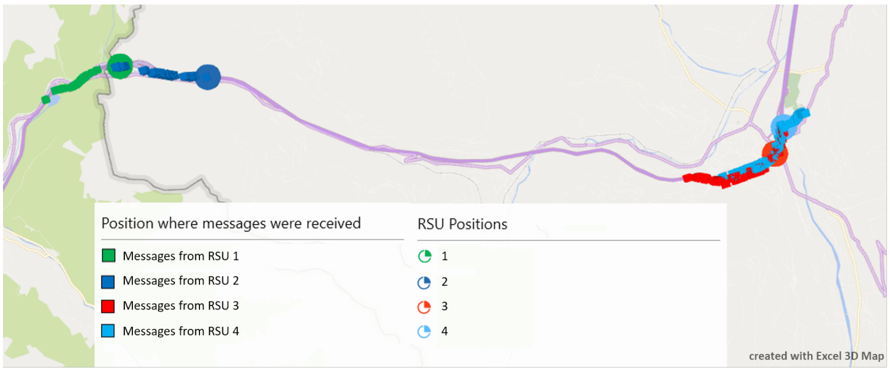


Figure 5.12: The achieved network coverage between the Brenner and Stierzing on the A22

Table 5.3 shows the average CAM frequency and standard deviation for CAMs received in a 200 meter radius from the RSU position. The number of CAMs that meet this criteria can be found in sample size. the maximum distance between sender and receiver for every RSU. All of them sent DENM (1), CAM (2) and IVIM and used C-ITS version

RSU	avg. f_{CAM} (Hz)	SD f_{CAM} (Hz)	SD sample size	max range (m)	messageID	version
1			0	1801	1, 2, 6	1
2			1	2117.5	1, 2, 6	1
3	0.24	0.20	4	2902.5	1, 2, 6	1
4	1.00	0.00	62	3283.7	1, 2, 6	1

Table 5.3: Average CAM frequency and standard deviation, sample size, range, protocols and C-ITS versions sent per RSU in Italy

1. Since no CAMs have been received from RSU 1 in the 200 meter radius used for the average cam frequency in Chapter 5.1 and Chapter 5.2 the f_{CAM} was not calculated. From RSU 2 one CAM was received in the 200 m range, therefore also no f_{CAM} could be calculated. Additionally, for RSU 3 the average and standard deviation of f_{CAM} was calculated, however only four messages were received in the 200 meter radius defined above. The sample size for RSU 4 is so large because the test vehicle had to stop at a tollgate in range of the RSU.

Lastly, it is noticeable, that the InformationQuality parameter in DENMs is always set to 4, unlike to Chapter 5.1 and 5.1 where it was set to 2. The DENMs include rainy weather warnings and warnings for general traffic conditions and stationary vehicles. However, since it did rain [2] that day, it is not possible to determine if the precipitation warning was set intentionally.

5.4 Distance Measurement Under Optimal Conditions

For this test drive, the route (marked in orange) in the Figure 4.9 was driven four times. A photo of the RSU and the road can be seen in Figure 5.14. Results from all four trips are presented first, and then the focus is placed on a single one.

Before calculating the results, incorrect messages had to be discarded. These are often captured shortly before the connection is lost and contain incorrect data. Since it is known what the RSU is sending, sorting erroneous captures out is easy. Messages where the message ID, station ID or protocol version did not correspond to the set values were discarded.

Figure 5.13 shows the position of the RSU (green) as well as the cut off points (blue) and the maximum distance points (red) at which a message was received. The cut off points describes the last point at which all messages of the RSU were received consistently. Only a few meters after these points, the last messages are received before the connection is completely lost. In Table 5.4, the cut off distances and the maximum distances can are shown. The largest distance between the monitor set up and the RSU at which a message was still received is 891.2 meters. Table 5.5 shows the average maximum and cut off distance, including variance and standard deviation.

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[2] `https://www.wetter.com/wetter_aktuell/rueckblick/italien/brenner/ITOTA0013.html?sid=11129&timeframe=10y` accessed 17.03.2021

Figure 5.13: Map with the RSU position (green), the cut off points (blue) and the maximum distance points (red)

Figure 5.14: The RSU with the straight road ahead

In Figure 5.15, the data of one trip of the test track was used to show the development of the signal strength. In order to present the negative signal strength more intuitively, the *signal quality* was calculated by adding 100 to the recorded signal strength, which was in dBm. While the signal strength decreases linearly, this is not the case for the received messages. Received messages are shown in Figure 5.16. There, the number of received packets by distance is shown from the same trip. Between 0 and 50 meters the vehicle had to accelerate to the driving speed, therefore more messages were received. After that, the driving speed was kept the same and differs only by a few km/h. In Figure 5.16 it can be seen that the reception of messages does not slowly fade, but ceases quite suddenly and only a few messages are received after. This might be due to local circumstances which will be discussed in Chapter 6.

Round	Cut off		Maximum	
	Distance (m)	Signal Strength (dBm)	Distance (m)	Signal Strength (dBm)
1	829.5	-94	871.3	-96
2	828.4	-96	887.1	-99
3	820.0	-94	891.2	-97
4	826.3	-95	867.9	-96

Table 5.4: Distances and signal strength at the cut off points and the furthest packet received per trip

	Average (m)	Variance (m)	Standard Deviation (m)
Cut Off	826.0	17.9	4.2
Maximum	879.4	98.6	9.9

Table 5.5: Average, variance and standard deviation of cut off points and the furthest packet received

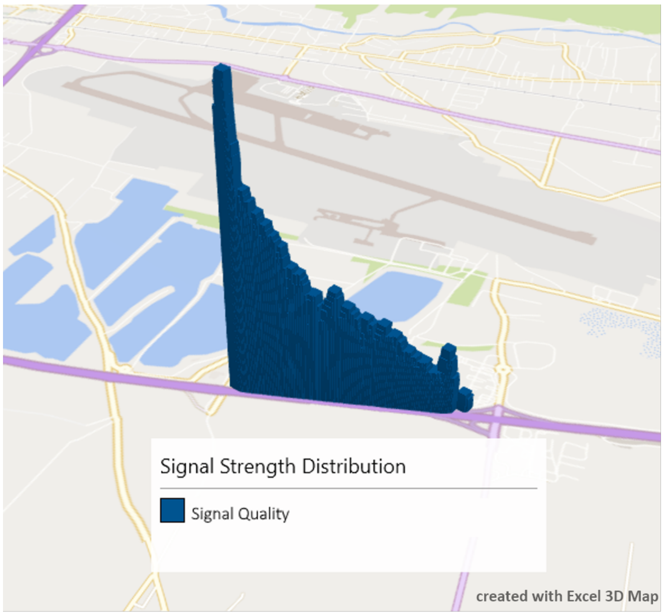


Figure 5.15: The signal quality degradation from the start left, to the stop right, at trip #2

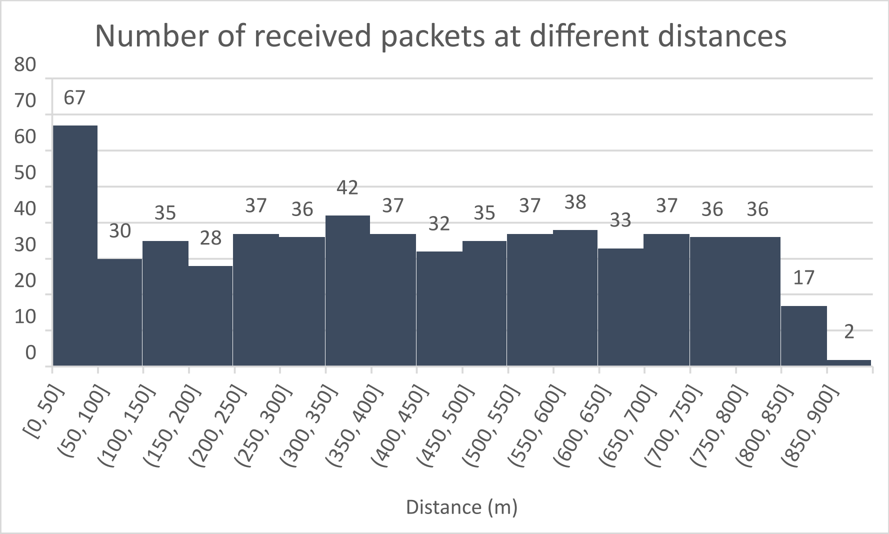


Figure 5.16: Histogram of the received packages at different distances of the car to the RSU

5.5 Distance Measurement in an Urban Environment

As described in Chapter 5.4, corrupt messages were filtered out first. Then the maximum distance and the signal strengths were examined. Here it is noticeable that the data differs in comparison to the optimal measurements with direct line of sight to the RSU in Chapter 5.4. These differences are summarized in Chapter 5.6.

Figure 5.17: Positions where a DENM packet was received with the RSU positioned at the ground

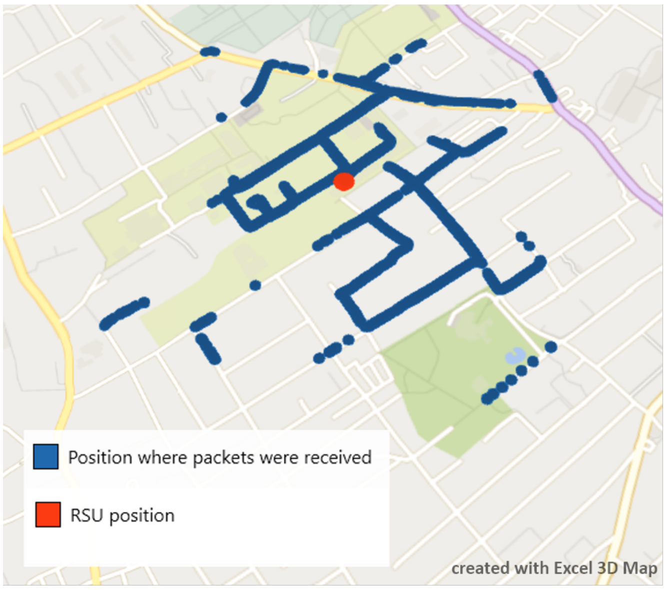


Figure 5.18: Positions where a DENM packet was received with the RSU positioned at the roof

	Max Distance
Urban Ground	250.8
Urban Roof	603.4

Table 5.6: The maximum distance between the RSU and the monitor where a packet was received

Figure 5.17 shows the points where at least one packet was received from the RSU while the RSU was positioned at the parking lot. In comparison, Figure 5.18 shows the received packets when the RSU was standing on the roof of the three-story building. Table 5.6 shows the maximum distances at which a correct message was received.

5.6 Signal Strength Comparison

For this chapter the signal strength progression was compared between Chapter 5.4 and 5.5. This progression can be seen in Figure 5.19. In Table 5.7 the co-variance and correlation between the distance of the RSU and the monitor and the signal strength is listed.

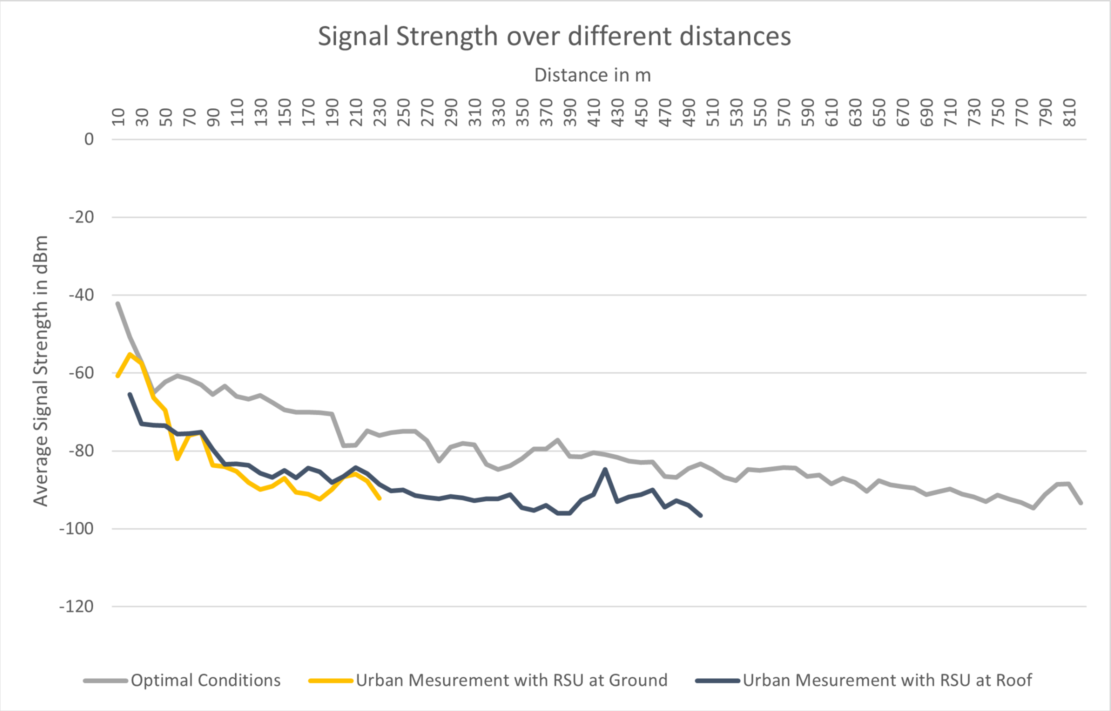
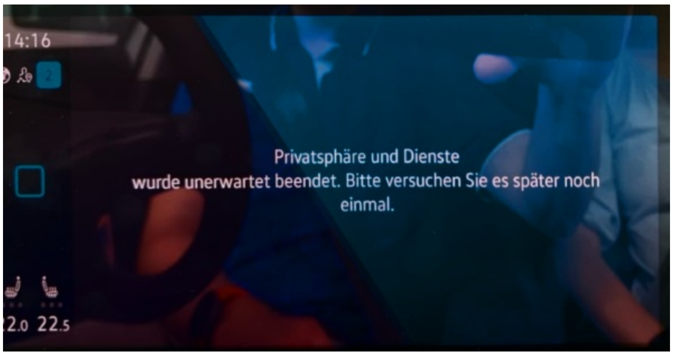


Figure 5.19: Signal strength degradation over growing distances

	Covariance	Correlation
Optimal Conditions	-2701	-0.9
Urban Ground	-707.7	-0.8
Urban Roof	-570.5	-0.6

Table 5.7: The correlation and covariance between the distance and the signal strength of three test drives

5.7 Test Drive of a V2X Equipped Car



Privatsphäre und Dienste wurde unerwartet beendet. Bitte versuchen Sie es später noch einmal.

Figure 5.20: “Privacy and services was terminated unexpectedly. Please try again later.” - VW Golf 8 Error Message

For this test, the RSU was set up to send a DENM warning of a traffic accident. The monitor was used to record the behavior of the VW Golf 8. However, not a single CAM could be recorded from the Golf 8. Neither in standstill with active ignition nor in driving mode nor during a test drive on the road and highway. Overall, three different cars were tested. The system constantly failed and turned off the V2X services, the error message shown can be seen in Figure 5.20. A request to VW was never answered.

6 Discussion

This chapter will answer the problems formulated in Chapter 2 with the aid of the results presented in Chapter 5. This chapter will also deal with conspicuous results pointed out in Chapter 5.

6.1 The Actual Roll Out Status of ITS-G5

Since the roll out status can be measured on many parameters, this work focuses on three questions: (i) which types of ITS-G5 capable hardware exist in the field, (ii) what V2X functionality is implemented in the field, and (iii) how well does the implemented functionality work?

Many vendors sell ITS-G5 capable hardware, which is evident when using a vendor lookup on the MAC addresses of received V2X messages. In Graz (Chapter 5.1) and Vienna (Chapter 5.2) RSUs from Siemens have been deployed. Additionally, RSUs sending C-ITS Version 1 in Vienna are from MPL. Italy (Chapter 5.3) uses RSUs from Cohda Wireless. Hardware used by passenger cars could not be identified using a MAC vendor lookup.

A handful of V2X services are currently supported by RSUs deployed in Graz, Vienna, and Italy. Mainly, three different protocols are live: CAM, DENM and IVIM. In the city of Vienna MAPs, SPaTs and SSEMs are also sent. DENMs received in Graz and Vienna seem to contain only test messages. MAPs and SPaTs in Vienna are defined correctly and describe intersections, as shown in 5.8. Whether also the traffic light status is correctly implemented needs to be tested with another test drive. The RSUs in Graz and Vienna seem to be configured statically, as the current weather or traffic do not seem to influence DENMs. It is also an open question whether these RSUs react to incoming messages, e.g. if they forward incoming DENMs or react to SREMs.

In general, C-ITS works in a real-world environment. Messages can be received over a maximum distance of 2250 meters in Vienna, as shown in Table 5.2. The average driving speed at motorways does not seem to have an impact on message transmission. However, a stumbling block for correct RSU functionality seems to be the exact location an RSU is mounted to: the poor results in Chapter 5.3 could be caused by shieldings from infrastructure and reflections. Also, in Graz and Vienna, isolated RSUs seem to have problems sending messages. This can be seen in Table 5.1 when looking at RSU 9, from which only 3 CAM messages were received. In Vienna, only very few CAM messages were received from RSU 8 and 11, which can be seen in Table 5.2. In all these cases an unfavorable mounting position could lead to these results.

Lastly, the implementation of VW also seems to have its flaws. As shown in Chapter 5.7, no data could be obtained during the whole test with the VW Golf 8. Nevertheless, it cannot be concluded that the system never works. During the test drives in Graz and Vienna, multiple CAMs from passenger cars were received; however, it is impossible to tell which car brand and model sent those messages.

To conclude, ITS-G5 seems to be in a test phase in Europe at the moment. Although the RSUs are in place, many seem to be sending mostly test messages. Then again, the fact that different test sites use different C-ITS versions and in Vienna two are used seems to underline the statement further. Additionally, VW's implementation does not seem to be working flawlessly yet, which further confirmed that it is in a test phase.

6.2 How do Practical Applications Differ from Theoretical Specifications?

This chapter discusses the extent to which practical applications comply with the specifications. Three points have been noticed in Chapter 5: (i) the transmission of CAMs, (ii) the InformationQuality parameter in DENMs, and (iii) the specified position of RSUs.

The CAM transmission rules defined by ETSI in [14] are not adhered to by all RSUs. The standard [14] defines: *"Sending CAMs as part of the CA basic service shall be present in all ITS-S, which take part in the road traffic (vehicle ITS-S, personal ITS-S, etc.)."* In Vienna (Chapter 5.2) no CAMs were received from RSU 6, 10 and 13 as shown in Table 5.2, in Italy no CAM was received from RSU 1 as shown in Table 5.3. Additionally, as stated in Chapter 3.1.2.1, CAMs must be sent with a frequency of 1 to 10 Hz. All RSUs in Chapter 5, that we received CAMs from, seem to comply with this. Discrepancies in the results are due to interference, but looking through the data by hand, one can see that the attempt to transmit at 1 Hz was made. However, the question arises whether 1 Hz is enough on the highway. Many RSUs are affected by interfering factors, for example from RSU 9 in Table 5.1 in Chapter 5.1 only three CAMs were received. A higher transmission frequency would be especially important for cars on the highway since otherwise oncoming cars can hardly be registered at driving speed.

Secondly, the usage of the InformationQuality parameter is questionable. The parameter is set to 2 in Graz (Chapter 5.1) and Vienna, although only test messages are sent. The standard [16] does not define which level should be selected in which scenario. There is only the recommendation of Lubrich et al. This devalues the significance of the InformationQuality parameter.

Lastly, also RSU position seems to not always adhere to the standard. In Graz and Italy, the RSU positions change slightly with every message. This is to be expected if the position is read from a GPS module. In Vienna, however, the position that RSUs send is fixed and always the same for each message of the respective RSU. There is a "manual" bit in the GeoNetworking layer to indicate such behavior, which signals that the geographic address has been set manually. However, this bit is not set for the stations in Vienna. Additionally, as mentioned in Chapter 5.2 the location of RSU 11 might not be set to the actual position of the RSU.

In summary, it can be said that the tested stations mostly comply with the standard. However, it sometimes leaves leeway when considering the informationQuality parameter or the acceptable range of CAM transmission frequency. However, sometimes the definitions of the ETSI standards are not adhered to, for instance, when RSUs do not send CAMs at all.

6.3 What is the Real Life Performance of ITS-G5?

Since the real life performance of ITS-G5 can be linked to many different factors, this chapter focuses on three aspects: (i) the maximal transmission distance discussed in Chapter 6.3.1, (ii) the connection quality discussed in Chapter 6.3.2, and (iii) the missing checksum discussed in Chapter 6.3.3.

6.3.1 Maximum Transmission Distance

Maximum transmission distance is strongly dependent on the position of the RSU and how much the a direct line of sight between sender and receiver is obstructed. When looking at the Results in Graz and Vienna, a maximum distance surpasses 2 km; in Italy, even 3 km were possible. In these tests, the RSUs were usually mounted to overhead displays on motorways or next to traffic lights. In Chapter 5.4 the RSU was standing on the ground, and the maximum range was 890 meters, although then hedges obstructed the direct line of sight.. In the urban environment (Chapter 5.5) with lots of interferences, the maximum distance was 600 meters when the RSU was placed on the roof and 200 meters when placed on the ground.

When looking at the maximum distance possible, another question arises: what is the maximum distance between RSUs to achieve a continuous network coverage? According to Gräfling et al. RSUs should be placed every kilometer. This can be confirmed in Graz in Figure 5.2, RSUs with a distance less than one kilometer could provide continuous network coverage.

6.3.2 Connection Quality

For a reliable connection, the maximum achievable distance between sender and receiver plays a subordinate role since the packet receive rate is usually already relatively low when reaching the maximum distance. More important is what distances can be covered with a reliable connection. However, as seen in Italy (Chapter 5.3), this question cannot be answered by a number alone since different interference factors can influence the transmission. Sometimes no messages are received even in the smallest radius around the RSU. Therefore, the quality of the connection is examined in this chapter based on two parameters: (i) the packet drop rate and (ii) the signal quality.

In the campaign in Chapter 5.4, there is no packet drop up to a distance of about 800 meters when sender and receiver are positioned in a direct line of sight as shown in Figure 5.16. However, at that distance, the smallest objects in the direct line of sight lead to a very drastic packet drop, as shown in Figure 5.16. Here, bushes blocked the direct line of sight, which immediately lead to a drastic packet loss.

In contrast to the 800 meters without packet loss above, when looking at the signal strength as a connection quality indicator, V2X can cover about 300 meters when sender and receiver are in direct line of sight and about 90 meters when not. This claim can be made under the assumption that at least -80 dBm signal strength is needed for a reliable connection. For WiFi, for example, various sources state that a signal strength of -80 dBm is the absolute minimum for a connection [1] [2]. When applying this to V2X and looking at Figure 5.19, this threshold was reached at 90 meters when the RSU was placed on the ground in an urban environment and also when the RSU was placed on the roof. However the maximum distances (Table 5.6) are vastly different. This might be due to interference, less obstructions and antenna characteristics.

6.3.3 Missing Checksum

Lastly, it is noticeable that manual filtering of the messages is necessary in all tests. No checksum can be used to check messages for correctness. Each recipient must check and validate the received messages themselves. While this path was probably chosen for standardization, due to timing constraints, this could lead to erroneous data in messages, like a DENM that contains the wrong accident location.

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[1] `https://www.metageek.com/training/resources/understanding-rssi.html` accessed: 17.03.2021

[2] `https://www.screenbeam.com/wifihelp/wifibooster/wi-fi-signal-strength-what-is-a-good-signal/` accessed: 17.03.2021

7 Conclusion and Future Work

This chapter concludes the findings of this thesis and provides an outlook for future work. The conclusion can be found in Chapter 7.1 and future research topics are discussed in Chapter 7.2.

7.1 Conclusion

Currently, two competing V2X standards are trying to conquer the automotive market: C-V2X based on LTE and ITS-G5 based on WiFi. ITS-G5 has been around for ten years, and the associated standard from ETSI is still regularly updated. Many research projects and publications deal with the performance of ITS-G5. V2X technology has also received a new boost from the VW Golf 8, which is equipped with an ITS-G5 transmitter.

Since many of the existing publications show partly contradictory results and many of them are only simulations, this thesis aimed to determine the actual behavior of ITS-G5. This was realized by six different test drives. Two routes of the Asfinag in Graz and Vienna and one in South Tyrol were visited. Two further tests were set up with an RSU, and finally, an attempt was made to examine a real VW Golf 8.

The evaluation of the data shows that despite the last ten years that ITS-G5 has been around, the roll-out status is still in a testing phase. CAMs, DENMs, IVIMs, MAPEMs, and SPaTEM have been received. However, the content is mostly fixed and mostly does not adapt to current events. Furthermore, VW seems to have some problems with the V2X in their initial roll out.

The definitions in the standard are predominantly adhered to but leave some room for free interpretation. The work also shows that RSUs can send messages over a distance of one kilometer, should there be no transmission interference. If it is essential that no packets are lost, this distance must be reduced. Shielding and interferences constitute a significant problem, especially in urban environments. However, at the motorway, it is simply a matter of RSU placement, and in the city, smaller transmission distances are probably acceptable due to slower speeds and more stops.

7.2 Future Work

Evaluating the results, it becomes clear that two issues need to be addressed in future works: (i) testing of real-world congestion scenarios and (ii) adequacy of protocols in the context of autonomous driving.

In regards to congestion Mannoni et al. [46], for example, show the simulated behavior of ITS-G5 as a function over number of users per square kilometer, compared to C-V2X, ITS-G5 performs rather poorly. A real life analysis of the behavior of ITS-G5 at a higher receiver density would be interesting. How does the congestion control behave, and what influence does this have on the transmitters' range? Additionally, how many V2X-equipped cars can be expected on the road in the next ten years? Is a density of 200 transmitters per square kilometer even realistic in that time frame?

Regarding autonomous driving, it would be important to evaluate to what extent the data in C-ITS protocols are adequate for autonomous driving. Are the intersections' descriptions in MAP and SPaT messages sufficient, or would more data be needed? Can other autonomous driving use cases be supported by V2X? Moreover, how well are these new use cases already supported with the existing V2X protocols?

Bibliography

[1] *ETSI ES 202 663 V1.1.0 (2010-01) Intelligent Transport Systems (ITS); European profile standard for the physical andmedium access control layer ofIntelligent Transport Systems operatingin the 5 GHz frequency band.* Standard. Sophia Antipolis, France: ETSI, Jan. 2010.

[2] A. Jafari, S. Al-Khayatt, and A. Dogman. "Performance evaluation of IEEE 802.11p for vehicular communication networks". In: *2012 8th International Symposium on Communication Systems, Networks Digital Signal Processing (CSNDSP).* 2012, pp. 1–5. DOI: `10.1109/CSNDSP.2012.6292712`.

[3] W. Anwar, N. Franchi, and G. Fettweis. "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p". In: *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall).* 2019, pp. 1–7. DOI: `10.1109/VTCFall.2019.8891313`.

[4] T. T. Almeida et al. "IEEE 802.11p Performance Evaluation: Simulations vs. Real Experiments". In: *2018 21st International Conference on Intelligent Transportation Systems (ITSC).* 2018, pp. 3840–3845. DOI: `10.1109/ITSC.2018.8569676`.

[5] Fernando A. Teixeira et al. "Vehicular networks using the IEEE 802.11p standard: An experimental analysis". In: *Vehicular Communications* 1.2 (2014), pp. 91–96. ISSN: 2214-2096. DOI: `https://doi.org/10.1016/j.vehcom.2014.04.001`. URL: `https://www.sciencedirect.com/science/article/pii/S2214209614000151`.

[6] Christoph Sommer and Falko Dressler. "Introduction". In: *Vehicular Networking.* Cambridge University Press, 2014, pp. 1–11. DOI: `10.1017/CBO9781107110649.002`.

[7] *C2C-CC System: CAR 2 CAR Communication Consortium Manifesto Version 1.1.* Report. Braunschweig, Germany: CAR 2 CAR Communication Consortium, Aug. 2007.

[8] *Intelligent Transport Systems (ITS);Communications Architecture.* Standard. Sophia Antipolis, France: ETSI, Sept. 2010.

[9] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions.* Standard. Sophia Antipolis, France: ETSI, June 2007.

[10] *ETSI TS 122 185 V14.3.0 (2017-03) LTE;Service requirements for V2X services (3GPP TS 22.185 version 14.3.0 Release 14).* Standard. Sophia Antipolis, France: ETSI, Apr. 2017.

[11] *ETSI TR 103 300-1 V2.1.1 (2019-09) Inntelligent Transport System (ITS); Vulnerable Road Users (VRU) awareness; Part 1: Use Cases definition; Release 2.* Standard. Sophia Antipolis, France: ETSI, Sept. 2019.

[12] Christoph Sommer and Falko Dressler. "Inter-vehicle communication". In: *Vehicular Networking.* Cambridge University Press, 2014, pp. 38–105. DOI: `10.1017/CBO9781107110649.004`.

[13] Christoph Sommer and Falko Dressler. "Information dissemination". In: *Vehicular Networking.* Cambridge University Press, 2014, pp. 136–228. DOI: `10.1017/CBO9781107110649.006`.

[14] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service.* Standard. Sophia Antipolis, France: ETSI, Nov. 2014.

[15] Zachary MacHardy et al. "V2X Access Technologies: Regulation, Research, and Remaining Challenges". In: *IEEE Communications Surveys Tutorials* 20.3 (2018), pp. 1858–1877. DOI: `10.1109/COMST.2018.2808444`.

[16] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service.* Standard. Sophia Antipolis, France: ETSI, Nov. 2014.

[17] *Intelligent transport systems - Cooperative ITS - Dictionary of in-vehicle information (IVI) data structures.* Standard. ISO, Aug. 2015.

[18] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Facilities layer protocols and communication requirements for infrastructure services.* Standard. Sophia Antipolis, France: ETSI, Nov. 2016.

[19] *V2X Communications Message Set Dictionary* $J2735_202007$. Standard. SAE International, July 2020.

[20] *Intelligent transport systems — Cooperative ITS — Using V2I and I2V communications for applications related to signalized intersections.* Standard. ISO, June 2019.

[21] *Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary.* Standard. Sophia Antipolis, France: ETSI, Aug. 2018.

[22] *802.11p-2010 - IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments.* Standard. New York, USA: IEEE, July 2010.

[23] *802.11-1997 - IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications.* Standard. New York, USA: IEEE, Nov. 1997.

[24] Christoph Sommer and Falko Dressler. "Access technologies". In: *Vehicular Networking.* Cambridge University Press, 2014, pp. 106–135. DOI: `10.1017/CBO9781107110649.005`.

[25] *ETSI EN 302 663 V1.3.1 (2020-01) Intelligent Transport Systems (ITS); ITS-G5 Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band.* Standard. Sophia Antipolis, France: ETSI, Jan. 2020.

[26] *Dedicated Short Range Communications Report and Order.* Report and Order. Washington, USA: Federal Communications Commission, Feb. 2004.

[27] *ARIB STD-T109 700 MHz Band Intelligent Transport Systems.* Report and Order. Japan: ARIB, Feb. 2004.

[28] *ETSI EN 302 571 V2.1.1 (2017-02)Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU.* Standard. Sophia Antipolis, France: ETSI, Feb. 2017.

[29] *ETSI EN 301 893 V2.1.1 (2017-05)5 GHz RLAN; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU.* Standard. Sophia Antipolis, France: ETSI, May 2017.

[30] *ETSI EN 302 636-3 V1.2.1 (2014-12) Intelligent Transport Systems (ITS);Vehicular Communications; GeoNetworking; Part 3: Network Architecture.* Standard. Sophia Antipolis, France: ETSI, Dec. 2014.

[31] *ETSI EN 302 636-4-1 V1.4.1 (2020-01); Intelligent Transport Systems (ITS);Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality.* Standard. Sophia Antipolis, France: ETSI, Jan. 2020.

[32] *ETSI EN 302 636-5-1 V2.2.1 (2019-05)Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol.* Standard. Sophia Antipolis, France: ETSI, May 2019.

[33] *ETSI TS 102 894-1 V1.1.1 (2013-08) Intelligent Transport Systems (ITS);Users and applications requirements; Part 1: Facility layer structure, functional requirements and specifications.* Standard. Sophia Antipolis, France: ETSI, May 2019.

[34] *ETSI TS 103 175 V1.1.1 (2015-06) Intelligent Transport Systems (ITS);Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium.* Technical Report. Sophia Antipolis, France: ETSI, June 2015.

[35] *ETSI TS 102 687 V1.2.1 (2018-04)Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part.* Standard. Sophia Antipolis, France: ETSI, Apr. 2018.

[36] *ETSI TR 101 612 V1.1.1 (2014-09) Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium; Report on Cross layer DCC algorithms and performance evaluation.* Technical Report. Sophia Antipolis, France: ETSI, Sept. 2014.

[37] Li Feng. *V2X White Paper v 1.0.* White Paper. NGMN, June 2018.

[38] *3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Vehicle-to-Everything (V2X) services based on LTE; User Equipment (UE) radio transmission and reception (Release 14).* Technical Report. Sophia Antipolis, France: 3GPP, Mar. 2017.

[39] R. Molina-Masegosa and J. Gozalvez. "LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications". In: *IEEE Vehicular Technology Magazine* 12.4 (2017), pp. 30–39. DOI: `10.1109/MVT.2017.2752798`.

[40] *ETSI TS 136 201 V12.2.0 (2015-04) LTE; LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); LTE physical layer; General description (3GPP TS 36.201 version 12.2.0 Release 12).* Technical Specification. Sophia Antipolis, France: ETSI, Nov. 2018.

[41] *ETSI TS 136 300 V14.2.0 (2017-04) LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (3GPP TS 36.300 version 14.2.0 Release 14).* Technical Specification. Sophia Antipolis, France: ETSI, Apr. 2017.

[42] *ETSI TS 124 386 V14.0.0 (2017-05) LTE;User Equipment (UE) to V2X control function; protocol aspects; Stage 3 (3GPP TS 24.386 version 14.0.0 Release 14).* Technical Specification. Sophia Antipolis, France: ETSI, May 2017.

[43] *ETSI EN 303 613 V1.1.1 (2020-01) Intelligent Transport Systems (ITS);LTE-V2X Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band n.* Standard. Sophia Antipolis, France: ETSI, Jan. 2020.

[44] *ETSI TS 103 574 V1.1.1 (2018-11) Intelligent Transport Systems (ITS); Congestion Control Mechanisms for the C-V2X PC5 interface;Access layer part.* Technical Specification. Sophia Antipolis, France: ETSI, Nov. 2018.

[45] S. Eichler. "Performance Evaluation of the IEEE 802.11p WAVE Communication Standard". In: *2007 IEEE 66th Vehicular Technology Conference.* 2007, pp. 2199–2203. DOI: `10.1109/VETECF.2007.461`.

[46] V. Mannoni et al. "A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X". In: *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring).* 2019, pp. 1–5. DOI: `10.1109/VTCSpring.2019.8746562`.

[47] G. Naik, B. Choudhury, and J. Park. "IEEE 802.11bd 5G NR V2X: Evolution of Radio Access Technologies for V2X Communications". In: *IEEE Access* 7 (2019), pp. 70169–70184. DOI: `10.1109/ACCESS.2019.2919489`.

[48] Yu Shengbo. “Introduction of China C-V2X Industry and Standards”. In: *China Society of Automotive Engineers(CSAE)* (). URL: https://www.itu.int/en/ITU-T/extcoop/cits/Documents/Meeting-20200909-e-meeting/17R1_CSAE_Status-report.pdf (visited on 12/14/2020).

[49] Kelly Hill. “It’s official: DSRC is out, C-V2X and Wi-Fi-sharing is in at 5.9 GHz”. In: *RCR Wireless News* (Nov. 19, 2019). URL: https://www.rcrwireless.com/20201119/wireless/its-official-dsrc-is-out-c-v2x-and-wi-fi-sharing-is-in-at-5-9-ghz (visited on 12/14/2020).

[50] Andrew Turley et al. *C-ITS: Three observations on LTE-V2X and ETSI ITS-G5—A comparison.* White Paper. NXP, 2019.

[51] Qualcomm. *Accelerating C-V2X Commercialization.* Presentation. Qualcomm, 2017.

[52] John Walko. “Europe Looks to Open Up 6GHz Band for Wi-Fi”. In: *EET Asia* (Oct. 30, 2020). URL: https://www.eetasia.com/europe-looks-to-open-up-6ghz-band-for-wi-fi/ (visited on 12/14/2020).

[53] *ECC Decision (08)01 The harmonised use of Safety-Related Intelligent Transport Systems (ITS) in the 5875-5935 MHz frequency band.* ECC Decision. ECC, Mar. 2008.

[54] *V2X Stations on the A2 near Graz.* https://www.google.com/maps/d/u/0/edit?mid=1SGe--AREHa6njaSiatBPwF0LngJvGeU6&usp=sharing. Accessed: 26.02.2021.

[55] “IEEE Standard for Wireless Access in Vehicular Environments–Security Services for Applications and Management Messages”. In: *IEEE Std 1609.2-2016 (Revision of IEEE Std 1609.2-2013)* (2016), pp. 1–240. DOI: 10.1109/IEEESTD.2016.7426684.

[56] *Weather archive data from the test drive in Graz.* https://www.timeanddate.de/wetter/oesterreich/graz/rueckblick?month=9&year=2020. Accessed: 04.03.2021.

[57] Peter Lubrich et al. *EU EIP SA 4.1: Determining Quality of European ITS Services.* EU EIP Website. 2020.

[58] *V2X Stations in Vienna and on the S1, A4 and A23 motorways.* https://www.google.com/maps/d/u/0/edit?mid=1rTaTKPl5z_uAMi1nZMkRdtu-yD-zeAaO&usp=sharing. Accessed: 26.02.2021.

[59] *V2X Stations between Brenner and Stierzing on the A22.* https://www.google.com/maps/d/u/0/edit?mid=1gmEAyNnXEqOfzjHZM22iCIUNEkqztOfw&usp=sharing. Accessed: 26.02.2021.

[60] S. Gräfling, P. Mähönen, and J. Riihijärvi. “Performance evaluation of IEEE 1609 WAVE and IEEE 802.11p for vehicular communications”. In: *2010 Second International Conference on Ubiquitous and Future Networks (ICUFN).* 2010, pp. 344–348. DOI: 10.1109/ICUFN.2010.5547184.