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Deliverable D7.1:

Final Report on Field Test and Evaluation Results

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Contents

1 Scope

This document summarizes and evaluates field testing results of the ConVeX project. The executive summary highlights the most important achievements and findings of the project and lists key events, where practical results from the project were demonstrated.

Further chapters summarize performance aspects related to physical layer for V2V/V2I and relevant network aspects for V2N, the results of the use case work and the outcome of the simulation activities.

2 References

[1] ConVeX Project Deliverable D1.1, “Use Cases, Requirements, Performance Evaluation Criteria”

[2] ConVeX Project Deliverable D2.2, “Final ConVeX System Architecture Description”

[3] ConVeX Project Deliverable D3.1, “Comparative Analysis of Candidate V2X Radio Technologies”

[4] ConVeX Project Deliverable D3.2, “Radio Technology Performance Report”

[5] ConVeX Project Deliverable D4.1, “Roadside ITS-Station Specification”

[6] ConVeX Project Deliverable D5.1, “Vehicular ITS-Station Specification”

[7] ConVeX Project Deliverable D6.1, “Report on Lab and First Field Trials”

[8] ETSI TR 102 638 V1.1.1: "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions"

[9] ETSI TS 102 637-1 V1.1.1 (2010-09): “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 1: Functional Requirements”

[10] 5G-Connected mobility official website ”.Accesed January 30,2020, http://www.5g-connectedmobility.com.

[11] 3GPP TS 23.501 R15: “System Architetcture for the 5G System”

[12] 3GPP TS 23.707 R13: “Architecture Enhancements for Dedicated Core Networks”

[13] 3GPP TS 23.850 R11: “Study on roaming architecture for voice over IP Multimedia Subsystem (IMS) with local breakout

[14] See https://docs.fcc.gov/public/attachments/DOC-360918A1.pdf

[15] See https://iot.eetimes.com/the-5g-lobby-wins-eu-council-stops-wifi-standard-for-v2x/

[16] See http://www.5g-connectedmobility.com/

[17] See https://www.mobilemark.com/product/mag-59001575/

[18] see https://www.taoglas.com/product/magma-aa170-gpsglonassbeidou-magnetic-mount-antenna-2/

[19] See e.g. https://www.talleycom.com/images/pdf/antenna-spec-138-eco-2400.pdf

[20] ISO/TS 19321:2015 Intelligent transport systems — Cooperative ITS — Dictionary of in-vehicle information (IVI) data structures

[21] ETSI EN 302 637-3 Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service

3 Definitions and Abbreviations

3.1 Definitions

See definitions in the ConVeX System Architecture description ref [2].

3.2 Abbreviations

3GPP	3rd Generation Partnership Project
5G	5th Generation
A9	Motorway A9
ACC	Adaptive Cruise Control
APN	Access Point Network
AS	Application Server
BNetzA	Bundesnetzagentur (German Regulatory Office)
CACC	Corporative Adaptive Cruise Control
CAM	Cooperative Awareness Message as defined in ETSI a message vehicles issue in 1Hz to 10 Hz interval to send their at least position and heading to its surrounding using local communication
CDF	Cumulative Density Function
CP	Control Plane
C-ITS	Cooperative Intelligent Transport Systems
C-V2X DP	Cellular V2X Development Platform
Decor	Dedicated core
DENM	Decentralized Environmental Notification Message as defined in ETSI a message vehicles or infrastructure components send case any relevant warning shall be issued to nearby vehicles
EEBL	Emergency Electronic Brake Light (use case)
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UMTS Terrestrial Radio Access
EU	European Union
FCW	Forward Collision Warning
GNSS	Global Navigation Satellite System
HW	Hardware
ICMP	Internet Control Message Protocol
ICS	ITS Central Station
ITS	Intelligent Transport System
IVI	In-Vehicle Information as defined in SAE and CEN/ISO information on current (dynamic) sign display to be sent from infrastructure to vehicles
IVIM	IVI Message

IRS	ITS Roadside station
IVS	In-Vehicle Signage
KPI	Key Performance Indicators
LOS	Line-of-Sight
LTE	Long Term Evolution
MQTT	MQ Telemetry Transport
NLOS	Non-Line-of-Sight
OEM	Original Equipment Manufacturer
PC5	ProSe Communication reference point 5
PER	Packet Error Rate
ProSe	Proximity-based Services
PRR	Packet Reception Ratio
P-ITS-S	Personal ITS Station
R-ITS-S	Roadside Intelligent Transport System Station
RAN	Radio Access Network
ROI	Region of Interest
RSU	Roadside Unit
RTT	Round Trip Time
RV	Remote Vehicle
SAE	Society of Automotive Engineers
SPaT/MAP	Signal Phase and Time / Map Standard
SPID	Subscriber profile Id
SPS	Semi Persistent Scheduling
SW	Software
SWD	Shockwave Damping Service Deployment
TCC	Traffic Control Center
TTI	Transmission Time Interval
UE	User Equipment
UP	User Plane
V2C	Vehicle to Cloud
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
V-ITS-S	Vehicular Intelligent Transport System Station
VMS	Variable Message Sign
VRU	Vulnerable Road User

4 Executive Summary

The ConVeX project was founded to carry out one of the first trials of 3GPP LTE Release-14 C-V2X technology. This could be very successfully realized, implementing selected Use Cases covering the different components of C-V2X, i.e. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) direct communication, as well as Vehicle-to-Network (V2N) wide area communication.
In the initial project execution phase a set of relevant Use Cases was investigated in detail. Use Cases suitable for field evaluation were selected and a set of Key Performance Indicators (KPI) were defined. This work is documented in Deliverable D1.1 [1].
The Use Cases were implemented end-to-end: as a key component for providing the newly defined C-V2X direct communication on the PC5 interface, C-V2X Development Platforms (C-V2X DP) were used. The overall hardware and software architecture of the C-V2X equipment has been specified in Deliverable D2.2 [2].
The C-V2X DPs were integrated into Audi cars, which were providing vehicle information via the CAN bus to the DP as inputs and reacted to the outputs with audiovisual alerts on the Audi HMI according to the Use Cases. This vehicular ITS station has been specified in Deliverable 5.1 [6].
The DP was also taken as base of the Roadside ITS Station (RSU) for the implementation of the infrastructure side of the V2I Use Cases. The RSU architecture has been specified in Deliverable D4.1 [5]. The RSU was connected to a virtual traffic center to showcase how the C-V2X system would be embedded further. Also the V2N component was showcased: similar to V2V and V2I, the alerts transferred from a simulated traffic center could be seen on the Audi HMI.
Apart from the verification that the Use Cases are working reliably with the new C-V2X standardization and first implementation, the project was also showcasing them in public at overall three demo occasions inviting the audience for rides in the Audi Q7 cars to get a first-hand experience:

- Demo at Audi Drive Experience Center, Neuburg an der Donau, (July 4th, 2018): focus on selected V2V Use Cases, here in a controlled test track environment. As a specific novelty some Use Cases were also implemented for a Ducati motorcycle, showcasing the particular usefulness of C-V2X to reduce accidents and potential injuries and fatalities of motorcyclist. This was shown for the first time in Europe.
- Cross-Border demo around Schengen, Luxemburg (April 5th, 2019): on invitation of the German Federal Ministry of Transport and Digital Infrastructure to contribute to the project day of the newly opened cross-border testbed covering Luxemburg, France and Germany with the presence of overall five ministers from all these countries, the ConVeX project showcased V2V and V2I Use Cases in cross-border scenarios, proofing the usefulness of direct communication without the need of mobile networks, since such border scenarios would pose roaming challenges and create periods of unreachability when using “classical” mobile networks. This was the world´s first cross-border demonstration of C-V2X direct communication. Also worth noting is, that the Use Cases were shown driving on open motorways and rural streets, i.e. within the normal traffic.
- ConVeX C-V2X Technical Workshop and Demonstration, Nuremberg, A9 Motorway (October 16th, 2019): seen as the closing event for the ConVeX project, a selection of Use Cases was shown covering V2V, V2I, and also V2N. The invited

audience came from road operators and authorities, car manufacturers and automotive engineering companies, and as a novelty an RSU V2I Use Case combination was shown, where the RSU probes the speeds of oncoming cars via C-V2X and reacts accordingly with dynamic speed recommendations. Also at this demo the applicable Use Cases were shown within the open traffic of the motorway.

The following Use cases have been successfully implemented, demonstrated and extensively tested by the ConVeX project:

- Blind Spot Warning/Lane Change Warning (BSW/LCW)
- Emergency Electronic Brake Light (EEBL)
- Intersection Movement Assist (IMA)
- Left Turn Assist (LTA)
- Slow/Stationary Vehicle Warning (SSVW)
- In-Vehicle Information (IVI)
- Roadworks Warning (RWW
- Follow Me Information (FMI)
- See Through (ST)
- Range Extension by Cellular Communication (RECC)
- Shock Wave Damping (SWD)

A main focus of the project was the investigation of the Physical Layer performance of the newly introduced C-V2X Side Link direct communication using the PC5 interface. An overview of 802.11p-based technologies and LTE for V2X, both the cellular LTE radio technology and sidelink technology has been presented in Deliverables D3.1 [3] and D3.2 [4]. We have compared side-by-side key features of their physical layers and analyzed their performance based on simulations.
The specifications of C-V2X within 3GPP Release 14 were only finalized by March 2017, but the ConVeX project had early access to prototype hardware and software, that were used during the entire project (C-V2X development platforms based on the Qualcomm 9150 C-V2X chipset). Tests addressing the key performance indicators of interest were carried out for different scenarios seen as relevant for C-V2X. While the results of our first field testing activities was already documented in Deliverable D6.1 [7], the present document complements D6.1, reports the final C-V2X field testing results, and provides overall an overall performance evaluation of C-V2X technology and assessment of its suitability to cope with real conditions of use.
The following high-level results could be proven:

- Range and reliability in Line-of-Sight conditions: more than 1.2 km for V2V (limited by the length of the street that could be found for the testing)
- Error free communication at relative vehicle speeds of up to 430 km/h (limited by other traffic participants. These tests were performed on the A9 and A6 motorway in early morning hours)
- Functional verification of the V2I communication for a typical deployment of an RSU on a bridge to cars on a motorway. Range of such a communication varies depending on several factors like morphology, obstructions and street bends (which causes loss of line-of-site conditions at some point).
- Urban range tests of V2V communication showed at least 140m range around completely “blind” intersection corner

Combining the radio performance results with the KPI requirements of the implemented Use Cases, one can conclude that all of them are supported by the C-V2X technology in all relevant traffic scenarios. This proves the maturity of C-V2X technology, even already very short time after availability of the 3GPP specifications and with employing first prototype Hardware and Software implementations.

In the meantime, C-V2X has been selected in China as the mandatory technology for new vehicles.

In the US, the FCC has proposed to assign a certain 20 MHz portion of the 5.9 GHz ITS band for safety-related C-V2X services [14]. C-V2X technology is backed in the US by many automakers including Ford, Audi, BMW, Daimler, and Tesla. Ford US has announced usage of C-V2X in all new cars from calendar year 2021.

In Europe, the European Council of ministers in July 2019 reversed a Commission decision to support the 802.11p based ITS standard for vehicle to everything (V2X) communication in the EU [15]. Due to strong support by car manufacturers, mobile network operators, chip manufacturers and other stakeholders, it looks very promising that C-V2X technology will also be rolled out all over Europe, taking profit from the current deployment of 5G mobile systems.

During the project several possible future work areas were identified and some more details and which these might be is presented in chapter 8.

5 Summary on Field Test Results

5.1 PC5 Physical Layer Performance Measurements (V2V/V2I)

5.1.1 Introduction

Within the ConVeX project, different scenarios that are relevant for C-V2X were investigated, with a specific focus on its usage for traffic related Use Cases. It was attempted to get indications of KPI values of general interest, e.g. the maximum reliable communication range or the impact of high vehicle speeds, and if the design targets are already met by the first implementations. Starting from the focus on more “physical layer related” performance measurements, which are summarized in this chapter, it is furthermore evaluated how this performance translates to feasibility of Use Cases, i.e. whether there are any limitations seen, or are the Use Cases supposed to work in any environment that is relevant for them.

The quality measure for communication between two devices or traffic participants is the successful reception of data, which is typically expressed by either the Packet-Reception-Rate (PRR) or the Packet-Error-Rate (PER), where PER[%] = 100 - PRR[%]. Here as data the CAMs were taken, i.e. the evaluation happens on ITS message layer, comparing what is sent by one participant and received by the other (logs taken on both sides). Since these messages are the actual building block of the entire system, this approach seems to be accurate.

5.1.2 Measurement Setup

In most cases, the measurements were performed with two cars (Audi Q7) equipped with C-V2X DPs (see e.g. Figure 5-1) and the following **Antenna system:**

Antennas for C-V2X PC5 (5.9 GHz) communication:

- 2x MobileMark MAG6 5900/1575 [17], mounted on vehicle rooftop
- Non-removable connector cables attached to the antennas with attenuation of 2.5 dB
- Omnidirectional antenna gain of 6 dB.

Antenna for GPS signal reception

- 1x Taoglas AA.170.301111 [18], mounted on vehicle rooftop

A typical antenna setting is shown in Figure 5-1. It should be noted that the exact location of the GPS antenna on the rooftop (in this example placement in the middle between the MAG6 C-V2X antennas) has no impact on C-V2X performance.

Figure 5-1: Installation of C-V2X reference and GPS antennas on vehicle rooftop

Transmit power
The default setting of PA output power is 21.5 dBm (i.e. nominal peak power of 23 dBm reduced by 1.5 dB MPR backoff for QPSK modulation; would be 2 dB for 16QAM). Given a cable and connector loss of about 2.5 dB and an antenna gain of 6.0 dB
the resulting maximal EIRP in case of QPSK modulation is

21.5 dBm – 2.5 dB + 6.0 dB = 25.0 dBm

ITS message size: regular CAM, with a size of 93 Bytes. Periodicity: 100 ms. The ETSI ITS stack from Savari is used here. These get transported on physical layer using MCS5, 12 RBs, QPSK modulation. (chosen physical layer parameters depend e.g. on payload that needs to be transmitted. This is done by the UE dynamically and in accordance with 3GPP standards. The implementation has commercial grade, however some more physical layer parameter choices are fixed now by standardization bodies as reference configurations). One (blind) HARQ retransmission is activated, i.e. each ITS message is transmitted twice on the physical layer.

Used Frequency: 5.92 GHz, 10 MHz bandwidth (frequency assigned by BNetzA to ConVeX for testing purposes at the upper border of the ITS band)

5.1.3 LOS Communication Range

Measurements of the communication range for a V2V setup in Line-of-Sight (LOS) radio conditions should be assessed under open-space and flat terrain conditions. This poses some challenges to carry out respective tests, since due to the large communication range for C-V2X of 2000 m or more as seen in other measurement campaigns a straight and wide enough street would be needed with a length in that magnitude. As described in deliverable D6.1 [7] various locations were tested – the longest straight road stretch that could be found and used was 1.2 km long.

Figure 5-2: Drive Route for LOS range test (Nuremberg area)
Picture source: Google Maps, © 2009 GeoBasis-DE/BKG. ©2019 Google

Test procedure:
One car is parked stationary at a fixed position and a second car is driving with a speed of about 10 km/h until the end of the test route. There, it is turning and then driving towards the stationary car with the same speed. As outlined in Section 5.1.2, both DPs are transmitting CAM with 100 ms periodicity and the successful receipt of these messages on the respective other DP is evaluated
Test result:
For this test location, the communication between the cars was quasi error free over the entire drive route: Figure 5-3 shows the Packet-Error-Rate (PER) over the distance of sender and receiver calculated with 5 m binning. Each spike corresponds to a single lost message within this binning, i.e. overall 5 messages were lost over the entire stretch of 1.235 km. Note, that at the end of the route, the communication is error free, i.e. the range measurement is limited by the length of the street, there was no visual impact to the C-V2X communication reliability because of the distance. This was a consistent finding also for the other locations investigated (another three straight roads were tried, which turned out to show obstructions due to bends or elevation changes after about 1 km).

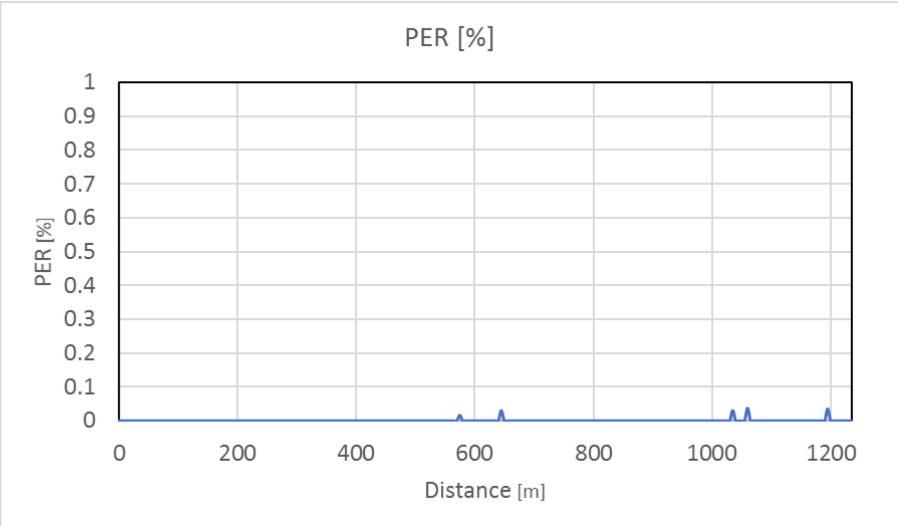

Figure 5-3: Measured PER on drive route shown in Figure 5.2

The ConVeX project attempted to get access to an airfield close to Ingolstadt (Manching), that should provide the possibility of extended range testing, but unfortunately this was finally not allowed by the responsible authorities.

5.1.4 LOS Communication Range – V2I (RSU – car)

For the case of the communication of an RSU with a car, a scenario was evaluated where the RSU was positioned on the railing of a bridge over the A9 Motorway at Nürnberg-Feucht (Josef-Schlösser-Weg), and the car is driving on the A9 (the same location was used for an implementation and test of the V2I Use Cases). The red star in Figure 5-4 indicates the RSU, which was mounted on the southern railing above the grass left of the motorway in order to avoid any danger of dropping installation material onto the A9 with its live traffic. The RSU is based on the same C-VX DP like used in the car, one difference of the setup is the used antenna – here one dipole antenna (MobileMark ECO12-5800, 12dBi gain [19]), which was indicated as a currently typical deployment. For the assessment of the communication range the CAM from the car received at the RSU were evaluated, and for the other direction the received DENM, that are carrying a Roadworks

Warning message. The used DENM has a size of 132 bytes (bigger than the CAM with 93 bytes, but still in the same magnitude). On physical layer it was transported using MCS4 and 18 RB using QPSK modulation. The seen distances were in line for both directions, which is according to expectations. Plotted on the Google Earth view as black dots are the locations of the car here travelling in northern direction, when the CAM is successfully received by the RSU. The communication gets over 90% PRR about 550 m before the bridge with the RSU. The first location from where the CAM is received is 920 m away – here the reception is spotty, and as one can see, there is a massive bridge in the communication path (B8 with four lanes crossing the A9). The error free communication continues for about 920 m after the RSU location to the north, and with some smaller interruptions it can be seen until 1065 m from the bridge. The motorway is making a curve to the right – and the direct communication path leads therefore through the trees next to the motorway, i.e. line-of-sight is obstructed. For the car travelling in south direction, the error free communication starts about 970 m before the RSU location, and continues until 620 m after it, getting a bit spotty from there until the big bridge at about 800 m distance. Furthermore, a small spot can be seen at a distance of 925 m, where the signal seems to have managed to pass the big bridge. Figure 5-5 shows for comparison the plots for a drive in southern direction (left picture) and northern direction (right picture): the error free communication area is slightly shifted to the south for the southern direction, and also the sharper start can be seen (no spotty area in the north).

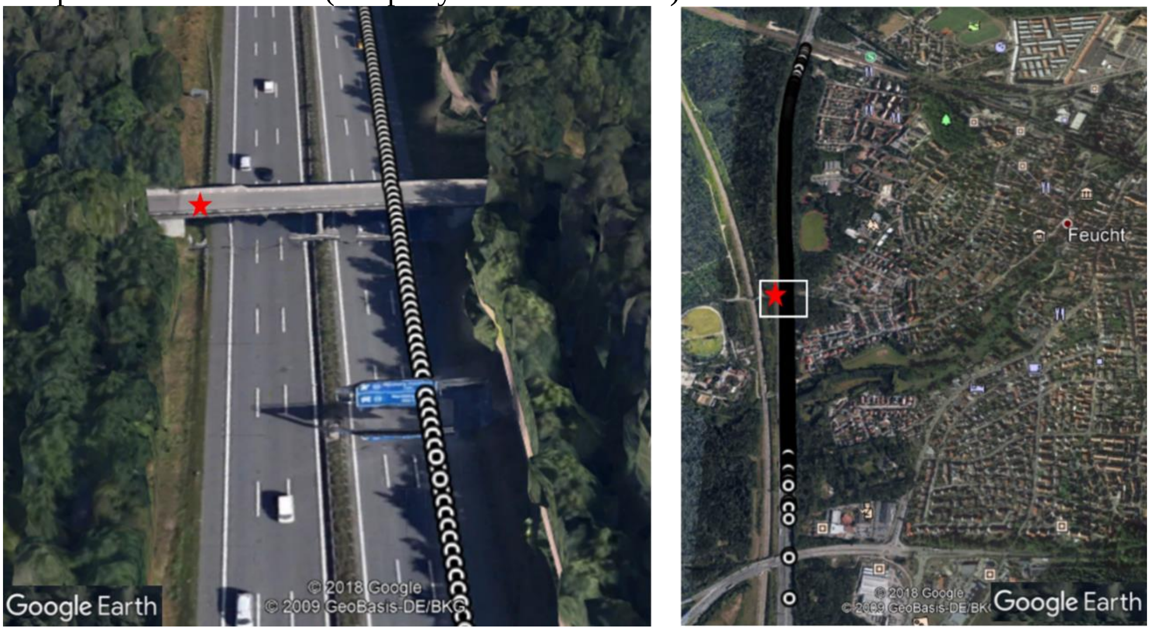

Figure 5-4: Communication of an RSU on bridge over A9 to a car on A9
Picture source: Google Earth, © 2009 GeoBasis-DE/BKG. ©2018 Google

It should once more be noted, that here a realistic deployment is tested, which means that there are also other obstructions like gantries (see example in the vicinity of the RSU location), or other vehicles (cars or specifically trucks). Furthermore, the terrain is not completely flat. The seen communication range underlines the feasibility of C-V2X for a real-world deployment. If needed, there are optimizations possible, e.g. for the placement of the RSU, or potentially the usage of directive antennas as well as employing diversity. Of course, this needs to be investigated in connection with the actual target or Use Case that shall get supported that would determine the desired communication range from the RSU position.

Figure 5-5: Comparison Communication with RSU driving south (left) and north (right)
Picture source: Google Earth, © 2009 GeoBasis-DE/BKG. ©2018 Google

5.1.5 NLOS in Urban Environment

For assessing the performance in an urban environment, which is of particular interest for the C-V2X usage and Use Cases, different, quite challenging test locations and setups were selected. Most of these tests were done in a part of the City of Nuremberg, with about five level high buildings that are built side-by-side, have no gardens but are directly at the pedestrian pavement, with narrow streets with one lane per direction, and parked cars at both sides (Nuremberg-Maxfeld). This kind of urban settlement can be found in many cities in Germany, as well as Europe in general, making it relevant as an exemplary urban traffic environment and thus for the testing.

Figure 5-6: Typical Road and Building Development in Nuremberg-Maxfeld
Picture source: Google Earth, © 2009 GeoBasis-DE/BKG. ©2018 Google

The testing was executed in a way, that one Audi Q7 vehicle was parked at a regular parking spot along the street, i.e. there were also cars parked in front and behind, keeping a distance from the next intersection, and the other Q7 vehicle was moving around on a selected street orthogonal to it. From RF point of view, this is a very challenging Non-Line-of-Site (NLOS) scenario. The speed of the moving car was in the range of 15 km/h to 30 km/h. The latter is in line with the speed limit of this urban area, however due to the small streets, a higher speed would also not be possible. Furthermore, worth noting is also the presence of other cars or even delivery vans during the tests, i.e. normal traffic was ongoing. The overall idea of the testing was to have a realistic situation that cars in such an urban environment will face. The evaluation performed was to assess from which location the moving car can get error-free communication (reception of the CAM) with the parked car.

1) Maxfeld open T-Intersection

In this scenario the stationary car is parked on the right side of the street at a distance of about 50 m from the intersection (see Figure 5-7: parking position is indicated by the yellow pin, distance to the intersection by the yellow line). The HV goes counterclockwise around the block – the street of interest for the measurements is the lower one, which is travelled from left to right (see orange arrows indicating the direction of travel). The green area below the street is a park (Nuremberg Stadtpark) with some trees especially towards the street. There are no buildings on that side of the street, so it can be seen as an open space, which should not cause many reflections.

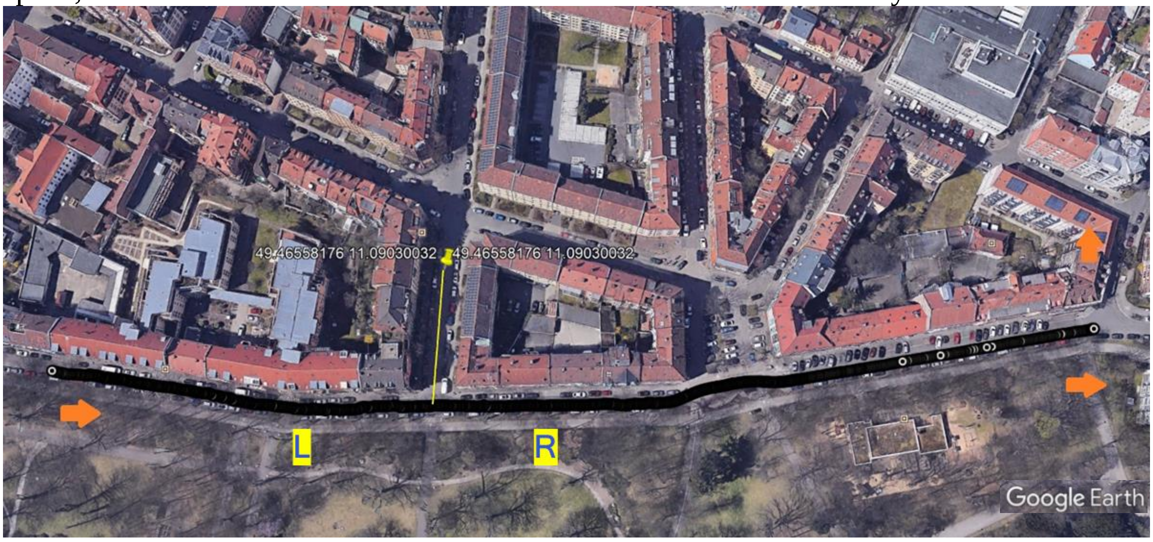

Figure 5-7: Urban Range Test Maxfeld open T-Intersection.
Picture source: Google Earth, © 2009 GeoBasis-DE/BKG. ©2018 Google

Each black dot on the map is indicating a successful receive of a CAM by the moving vehicle, building up here a continuous line for more than 100 m from each side of the intersection. For determining the communication range a limit of PRR >= 90% was taken. Table 5-1 summarizes the results for the different test iterations. The communication starts in the magnitude of more than 130m left of the intersection and continuous until for more than 160m to the right of the intersection, in one case even 265 m were reached. Note, that there might be dependencies with the actual additional traffic on the street.

Iteration	Left of intersection	Right of intersection
01	145 m	265 m
02	123 m	178 m
03	136 m	165 m
04	160 m	160 m
05	137 m	176 m

Table 5-1: Measured communication ranges – Maxfeld open T-Intersection

2) Maxfeld Closed Intersection

Here the stationary car is parked on the left side of the street in a distance of 85 m of the intersection (yellow pin), in this case a four-way-intersection with five level building at all sides of the streets. The HV goes counterclockwise around the block as indicated by the orange arrow. The street orthogonal to the one with the RV is travelled from right to

Figure 5-8: Urban Range Test Maxfeld closed Intersection.
Picture source: Google Earth, © 2009 GeoBasis-DE/BKG. ©2018 Google

left. Here the communication starts about 150 m right of the intersection and continuous in most cases until 140 m to the left of it, where the end of the street is reached – potentially it could continue but driving further on in this direction is not possible. Turning left at that corner, the communication breaks. Note, that although there is some bend on the right side, there is no impact on the communication (it might of course be the source of limiting the range).

Iteration	Left of intersection	Right of intersection
01	140* m	154 m
02	140* m	152 m

03	140* m	146 m
04	135 m	144 m
05	140* m	150 m

*end of street reached

Table 5-2: Measured communication ranges – Maxfeld closed Intersection

3) Maxfeld around the block

This test is an extension to see how the C-V2X communication looks like around a complete urban block. The RV is parked in the central street on the left side, again within a row of parked cars, and has a distance of 62 m to the upper street (marked with U) and 160 m to the inferior street (I). The HV goes counterclockwise around the block as indicated by the orange arrows, with a length of about 150 m for the upper, and 250 m for the inferior street, the outer streets are driven for about 230 m. As one can see from the black dots, there is very good communication coverage seen on the relevant quadrant area, even going around the outer corners. Note that also the middle cross is completely covered – this was assessed in a different test run not shown here. This means that for all streets where the HV could possibly turn and encounter the stationary RV, there is extended coverage before (blue arrows show some of the possibilities). This means respective warnings can be received timely or at a (more than) sufficient distance - e.g. for Use Cases like Slow Stationary Vehicle Warning (SSVW) or potentially Emergency Electronic Brake Light (EEBL).

Figure 5-9: Urban Range Test Maxfeld Around the Block.
Picture source: Google Earth, © 2009 GeoBasis-DE/BKG. ©2018 Google

4) Nordostpark open T-Intersection

This scenario should assess a more open intersection with a minor street leading to a main street. This was found at a business park in Nuremberg (Nordostpark). Along the main street there are bushes and trees, which are blocking the visual view to the cars on the main street. The RV is parked 100 m from the intersection on the left side of the street, and the HV goes clockwise around the business park, traveling from right to left on the main street, which is the area of interest for this test (see Figure 5-10). Speed limit here is 50 km/h, but the actual speed was dependent on the traffic, and in the range of 30 km/h to 50 km/h. The communication is starting 190 m to 200 m right from the intersection and continuous with a PRR >= 90% until about 200 m left from it. Note that at that position the direct line to the RV is getting blocked by a high office building (left part of the picture). There is a similar blockage at the right side – also here a higher office building is in the direct path. The little white square close to the parking position of the RV is a one floor high bakery shop (about 12 m x 12 m in size), which seems to have no visual impact to the communication, although it is blocking the direct path as well.

Figure 5-10: Urban Range Test Nordostpark open T-Intersection.
Picture source: Google Earth, © 2009 GeoBasis-DE/BKG. ©2018 Google

Iteration	Left of intersection	Right of intersection
01	194 m	191 m
02	193 m	192 m
03	212 m	200 m

Table 5-3: Measured communication ranges – Nordostpark open T-Intersection

Although measured inside the city limits, these results could also be extended to a rural traffic scenario, where in many cases minor streets are reaching the main street as an open T-intersection, with some vegetation along the streets.

Summary of the results

For the intersection scenarios, even in the very dense city scenarios, error free communication was seen at distances of at least 140 m from the intersection. As expected, the range differs with the density of buildings and the distance of the RV from the intersection. The test driving around the block also showed great ranges, covering the quarter streets, and providing extended communication around the outer corners.

Relevant Speeds and Distances
Taking the "rule of thumb" calculations, that are e.g. used for driving license questions:

$$\left(\frac{speed\ in\ km/h}{10}\right) \text{ x } \left(\frac{speed\ in\ km/h}{10}\right) = \textit{Braking Distance in m}$$

$$\left(\frac{speed\ in\ km/h}{10}\right) \text{ x } 3 = \textit{Reaction Distance in m}$$

Braking Distance + Reaction Distance = Overall Stopping Distance

one can calculate the following table for speeds that are relevant in Urban and Suburban/Rural traffic situations:

Speed	**Braking Distance**	**Reaction Distance**	**Overall Stopping Distance**
30 km/h	9 m	9 m	18 m
50 km/h	25 m	15 m	40 m
70 km/h	49 m	21 m	70 m
100 km/h	100 m	30 m	130 m

Table 5-4: Braking, Reaction and overall Stopping Distances for different Speeds

The braking distance is assuming "normal braking" – for emergency braking, half of the distance would be taken. (Re-calculating the formula for the braking distance, the actual value for the average deceleration used is 3.86 m/s^2, while a normal car doing hard braking can easily reach 7 to 8 m/s^2 on a dry street, thus the assumption of "normal braking" is correct, and the distances are on the conservative side). The reaction distance is based on a reaction time of about 1s in which the car is continuing to move on at the original speed without braking.
Taking the measured communication ranges of > 140 m into account, and the fact, that the basic safety use cases can be triggered as soon as a the communication is reliably working between RV and HV, one can derive, that even speeds in the range of 100 km/h would be supported. These speeds would not be possible or relevant in most of the urban scenarios, however this shows extra safety margins provided by the technology.
The tests were done with one stationary and one moving vehicle, but of course one could also see the distances as a certain snapshot of a traffic situation with two moving cars.

5.1.6 High speed Tests

As already described in detail in D6.1 [7], drive tests with high vehicle speeds were carried out at different highway locations. In this setup two cars are driving in opposite directions and they are coordinated in a way, that they meet each other at a rather straight segment of the road. Since the design target of C-V2X per 3GPP is to cope with relative speed of up to 500 km/h, one test objective was, that both vehicles drive at the highest speeds possible. It was possible to sustain a speed of more than 200 km/h for both cars during the test run, and have a maximum relative speed of 430 km/h. Since these tests were carried out in normal traffic (although in the very early morning hours), still some impacts to the maximum speed were given by other cars, since these tests should be executed safely.

Evaluating the sent and received ITS messages, it could be proven, that there was no visible impact from these very high relative speeds. The communication started basically

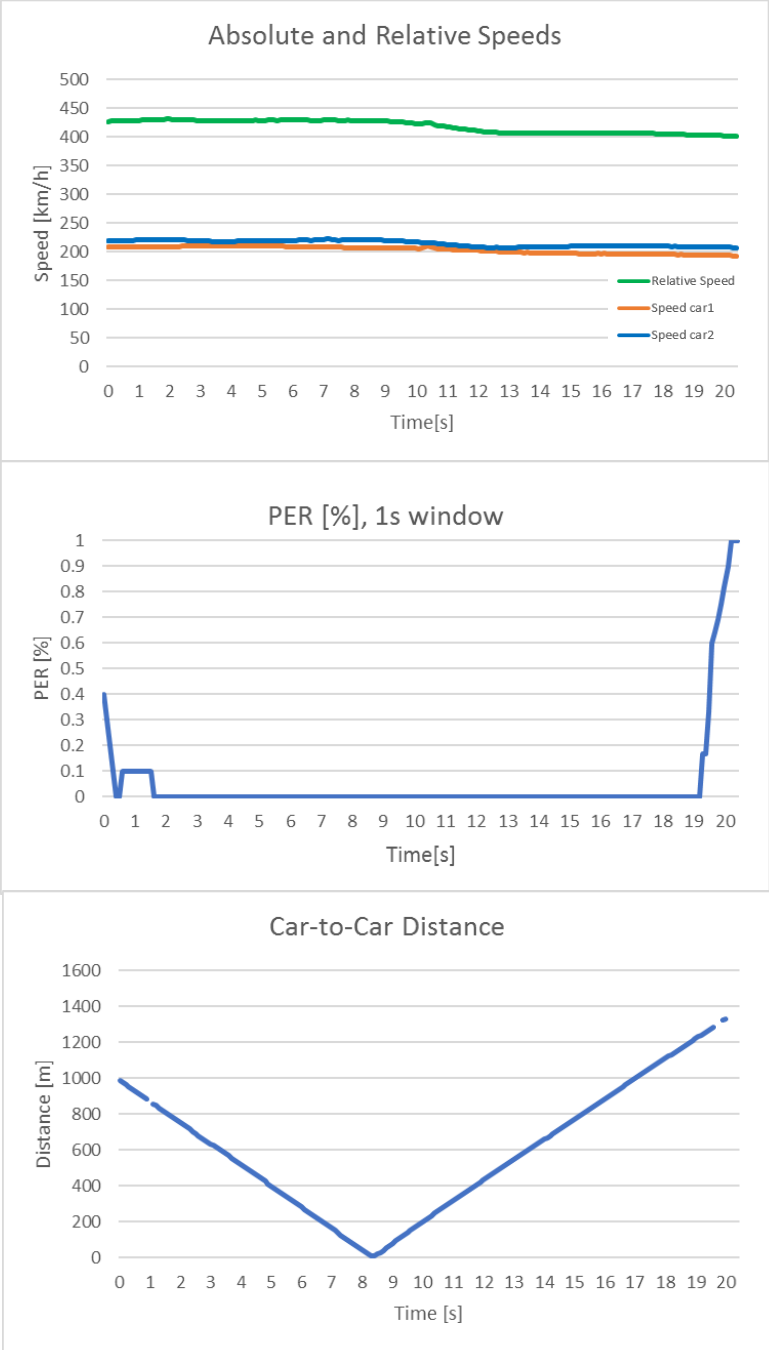

Figure 5-11: Result summary of High Speed Test

when line-of-sight conditions were established – for the shown result this was happening in the order of 1000 m and continuing nearly error free until these conditions are lost again (here at more than 1200 m inter-vehicle distance). Tests with lower vehicle speeds confirmed essentially the same range. Note, that the testing is carried out in a realistic Autobahn environment with e.g. bridges, traffic sign gantries or also trucks as potential obstacles.

The conclusion from these test results is, that C-V2X works at high speeds on the motorway with no impact to the reception of the exchanged CAM. If the range of more than 1000m and these high relative speeds are indeed needed has to be evaluated on a per Use Case base, however high speed is not a limiting factor, and the design target seems to be fulfilled.

5.2 Uu Performance Measurements (V2N)

5.2.1 Introduction

Vehicle to Network (V2N) communication allows vehicles to use cellular networks to connect to services hosted in the cloud. It can also be used to allow vehicles to communicate with each other in case direct communication (V2V) is not available. Various services can be offered to vehicles to increase safety and allow orchestration on the road. It can also offer additional edge-cloud based computational power to all vehicles. A central node can gather information from various vehicles in the area and suggest better maneuvers which can enhance the safety of all vehicles instead of depending on the limited sensor range that exist inside of a single vehicle.

During the time period of the project, the private LTE network operated by the 5G Connected Mobility Project (5G-CM) [16] was utilized to study the usage of the network for some selected ConVeX use cases. The testbed uses Band 28b (700 MHz), which has been granted as a test band by BNetzA, and which has been awarded to Telefonica for commercial use in the future. 10 MHz of spectrum are available for both UL and DL, with 2x2 MIMO configuration. The modulation scheme is 256QAM for DL and 64QAM for UL. Consequently, the estimated throughput is ~90 Mbit/s for DL and ~40 Mbit/s for UL. The network is covering a test-track on the A9 motorway between Nuremberg-Feucht and Greding in Bavaria. The length of the test-track is approximately 30 km covered by 6 base-stations. It also covers the town of Feucht. More details about the network setup can be found in D2.2 [2].

The availability of the test network on a real road allows a distinctive opportunity to conduct measurements. This can help us understand how the users will experience the V2X service in a real-world scenario.

We conducted measurements for latency between a moving vehicle and a remote server. The goal is to measure the latency induced by the radio while a vehicle is moving at high speed on the motorway, this measurement helps us understand the expected behavior when conducting specific use-cases that might require near-real-time latency. It also explains the effect of using some of the network features such as local-breakout and edge cloud. We also measured the throughput to analyze the maximum network capacity. In addition to that, we showed the effect of running parallel traffic using different network slices.

5.2.2 Network features

This subsection discusses two network features that are available in the test network, the features are network slicing and edge computing.

5.2.2.1 Network slicing

The importance of network slicing emerged from the diversity of services that can use 3GPP networks. Each service has potentially different requirements in terms of latency and bandwidth. However, all simultaneously employed services share the same resources in the operator network. Therefore, there should be a way to control resources and adapt them to allow fair division of resources.

Network slicing [11] **Error! Reference source not found.**allows the operator to create multiple virtual networks on top of the physical network. Each virtual network is mapped to one or multiple services that share the same connectivity requirements. An instance of

a virtual network is called a network slice. Each network slice has a set of network functions and resources that are made available for the service provider assigned to it. Each network slice can be fully or partially isolated from other network slices.
The network slicing (virtualization) is applied in an end-to-end fashion including both dedicated core (Decor) [12] network slice and RAN slice.

RAN slice:

RAN slicing is based on Radio resource partitioning, which is configured at the cell site. The RAN partitioning ensures a controlled sharing of radio resources between different slices. Each slice has a percentage of the available radio resources as shown in Figure 5-12

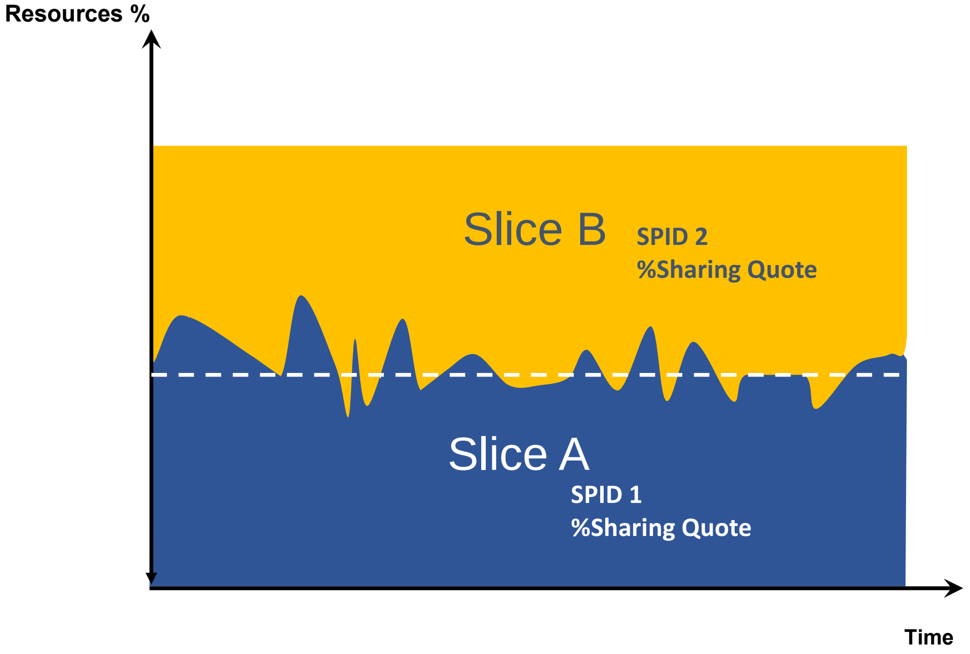

Figure 5-12: Radio resource sharing based on SPID

The process of sharing radio resources is dynamic. If there are any resources not used by a specific slice these can be shared among other active slices. However, each slice can reuse its configured shared quote when required. Resource usage is measured and adjusted every Transmission Time Interval of 1 ms (TTI). The slice assignment is based on the subscriber profile ID (SPID).

Core slice:

Core slice benefits from a feature in 3GPP called Dedicated Core Network (DÉCOR) [12]. It allows an operator to deploy one or more dedicated core networks. Each core is dedicated to a group of subscribers. It also allows the separation of resources for both, User Plane (UP) and Control Plane (CP). The core slicing is based on the Access Point

Name (APN), where each service is routed through a different APN assigned to it as shown in Figure 5-13.

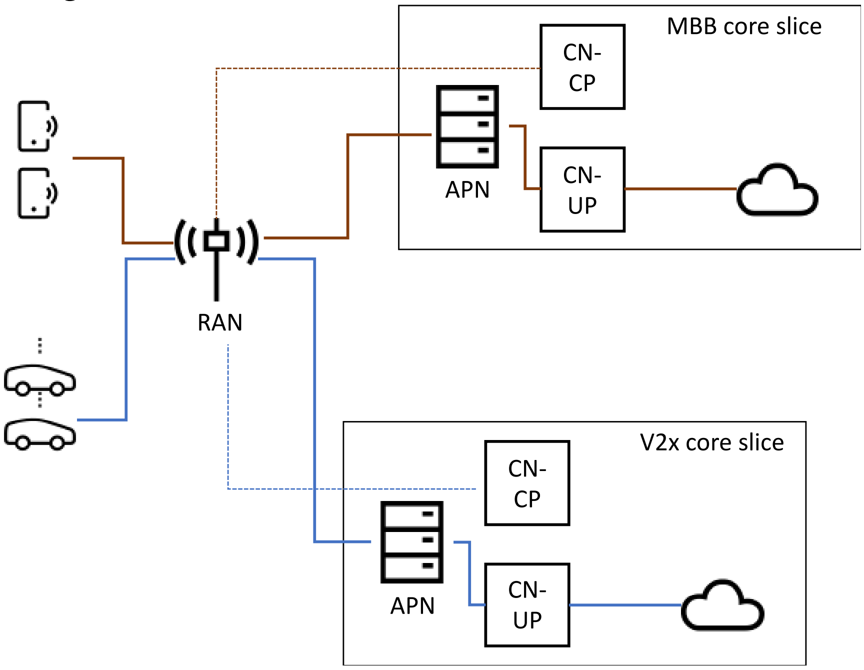

Figure 5-13: Slicing separation via APN

5.2.2.2 Edge computing

One of the features implemented in the A9 test field network is edge computing. The benefit is that it provides computational power very close to the location of the service users. It can host applications that can take advantage of reduced latency due to the short geographical distance between the users and the application server. It can also reduce the traffic in the core. This happens by directing the traffic directly to the edge without the need to transfer the data through the core to the gateway and then to the public internet. This feature is enabled by applying local break-out [13].

Figure 5-14 shows the architecture used in the test-track network. The control plane functions and the user-plane functions are separated. The control plane data processing is located in Aachen, while the user plane data processing is performed in Greding, i.e. in close neighborhood to the A9 test field.

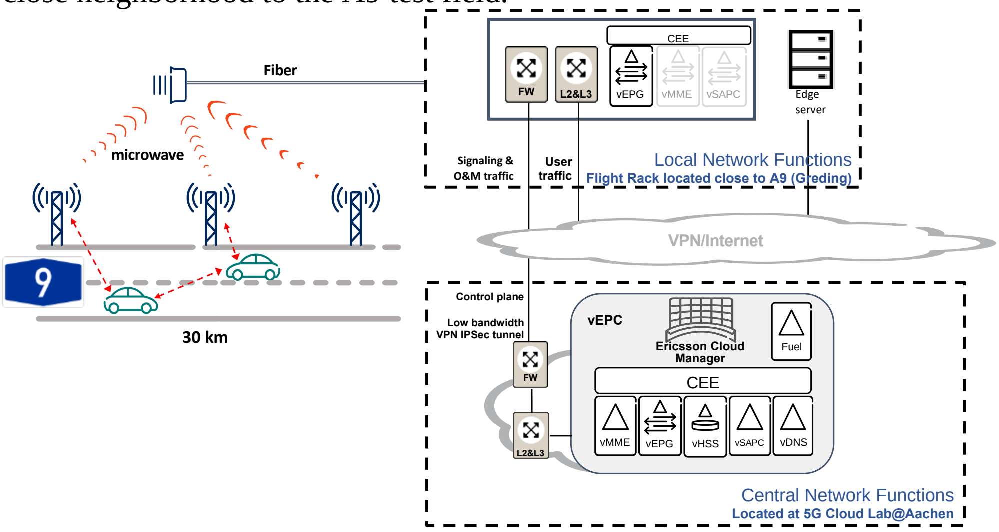

Figure 5-14 Network functions distribution in A9 test-track

5.2.3 Measurement

The following section covers the results of the measurements conducted along the A9 test-track.

5.2.3.1 Measurement setup

The measurements were conducted using 3 commercial UEs that supports band 28. Each UE is configured to connect to a different APN. The UE here could also represent any client that is embedded in the vehicle and support cellular communication. Each APN is linked to a different radio slice. Here, all E2E slices are connected to the same edge server. Therefore, it can be seen that the only difference between slices is the different RAN slice.

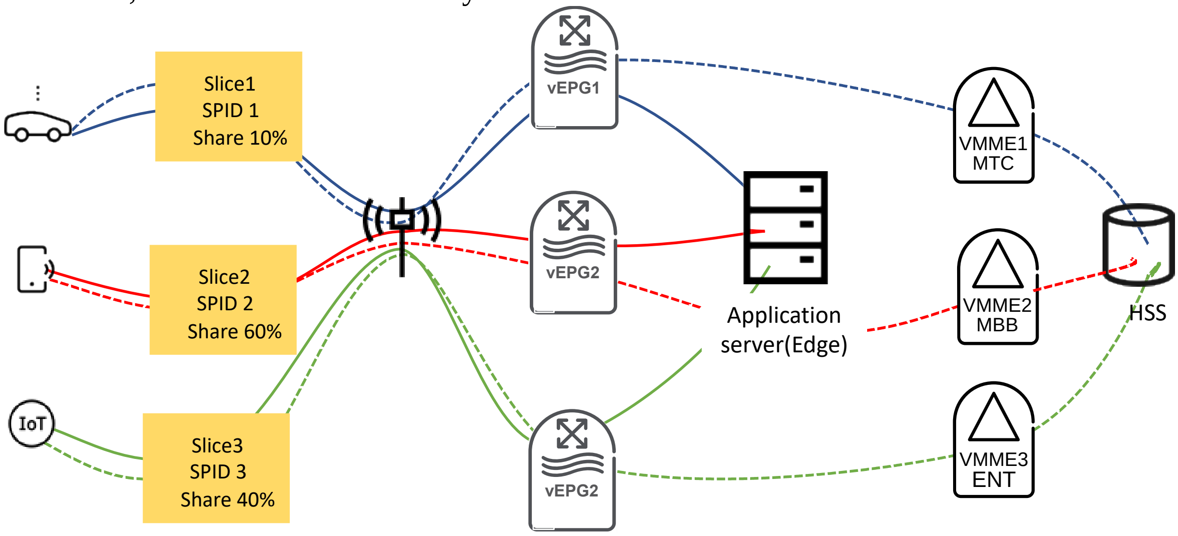

Figure 5-15 Slice configuration and connectivity to edge

The slices are configured as follows:

- Slice 1: Low latency slice. It is configured for a small amount of data. It takes 10% of the available bandwidth. The radio resources scheduling is configured to guarantee low latency E2E. Low latency provides an advantage for some V2X use-cases.
- Slice 2: Mobile broadband traffic. it has a higher bandwidth share (60%).
- Slice 3: Configured for a moderate amount of data (30% share).

The 3 UEs are mounted in a vehicle. We drove along the A9 test-track with an average speed of 120 km/h.

5.2.3.2 Results

5.2.3.2.1 Round trip time

Latency is an important factor that can affect automotive services. We assume that vehicles will always benefit from getting the latest information about the road ahead. However, the requirement for latency differs according to the type of information to be shared. For example, collision avoidance might require critically low latency values but sensor sharing, or incoming street conditions can have a more tolerant latency value.
In this section, we are measuring Round Trip Time (RTT) over two slices; slice 1 and slice 3. Where slice 1 RAN is configured for low latency, while slice 3 is using a default

configuration. RTT is measured using ICMP. The packet size is configured to 5 KB. Figure 5-16 shows the CDF for RTT. It can be seen that the specially configured slice has an average RTT of 23 ms, while slice 3 has an average of 35 ms.

We can conclude here that the delivery of hazard warning messages can be achieved in both slices. If we take the implemented "slippery road ahead" warning as an example, the shared information can be useful for the following vehicle. Since the LTE network has very little limitation on the range and network coverage, the network can deliver the warning ahead of time to ensure all impacted vehicles receive the warning.

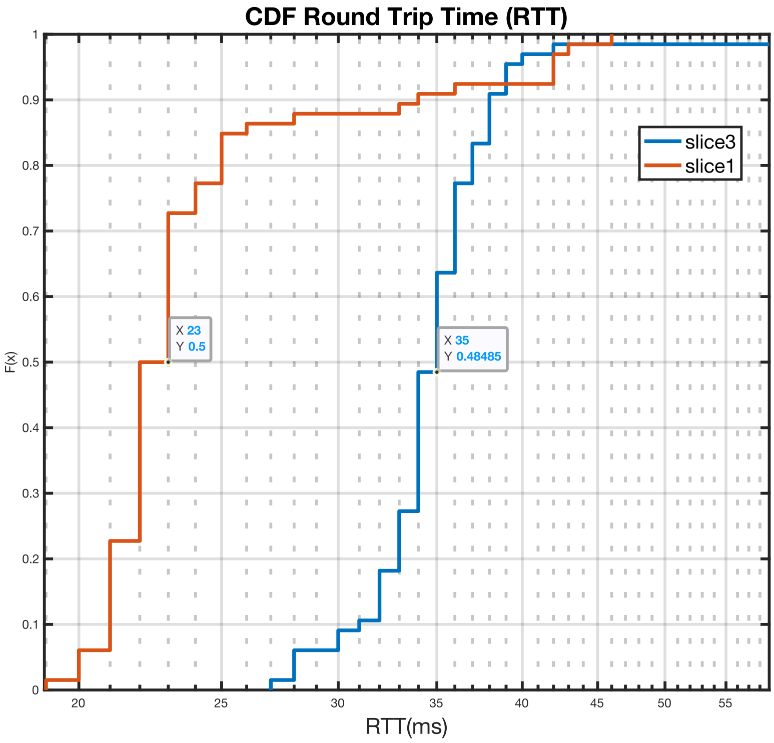

Figure 5-16: RTT CDF for 2 slices

5.2.3.2.2 Maximum throughput per slice

Network slicing is important to ensure fair resource partitioning between applications. During this measurement we had the 3 UEs, each assigned to a different network slice. Each UE downloaded data over TCP from the Edge Server using all available bandwidth. The purpose of this measurement is to show how different slices share the available resources without starving any slice.

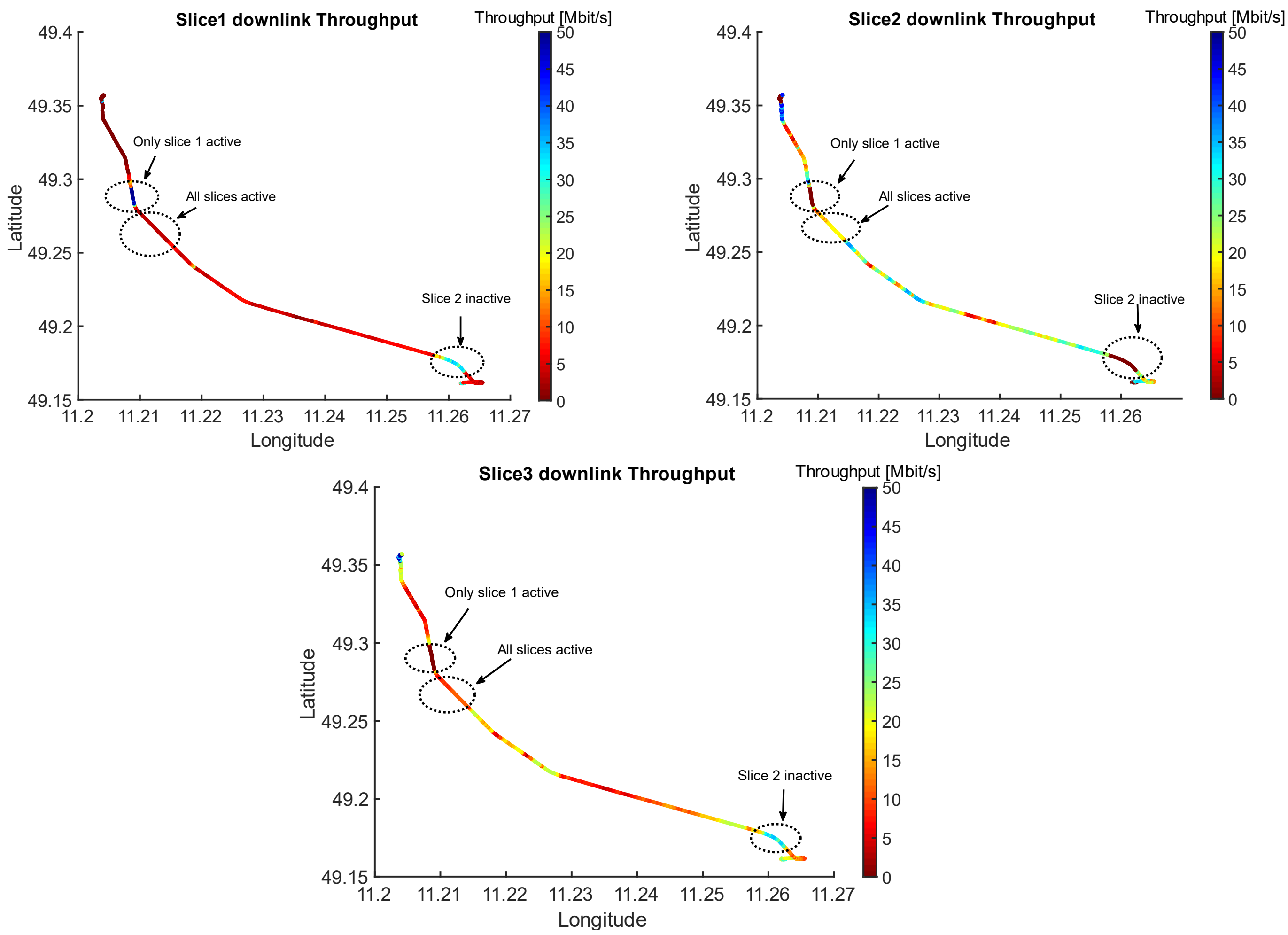

Figure 5-17: Throughput Share across 3 slices

Figure 5-17 shows the throughput for the 3 slices along a 30 km drive. It can be seen that the 3 slices are sharing the available throughput with reference to their preconfigured quota explained in section 5.2.3.1.Table 5-5 is showing the average bandwidth shared between the slices in different cases. The first case shows the 3 slices running in parallel. It can be seen that slice 1, slice 2 and slice 3 use 11.2%, 55.8% and 33% respectively. In the second case the UE that uses Slice 2 is deactivated. It can be seen that the resources released by the deactivated slice was shared across the other two slices with 52.9% for slice 1 and 47.1% for slice 3. The two slices shared the available resources almost equally. In the last case where only 1 slice is active, it can be seen that it has used 100% of the available resources.

It can be noted here that the maximum theoretical bandwidth of 90Mbps on downlink was not achieved. This is due to multiple factors; such as the type of the device used is not supporting the high 256 QAM modulation scheme, also interference plays a role in reducing the overall bandwidth. Also, the signal strength varies depending on the distance from the base station.

We can conclude that using network slicing, the automotive application can guarantee a steady performance without being affected by other background traffic. Also, when the automotive application is not using the assigned resources, they can be used by other applications running in different slices. It must be also noted that case 2 and 3 were both conducted at the end and beginning of the track, where the vehicle was moving very close to the BS. hence the average value of the achieved bandwidth is higher than when all slices where active.

Table 5-5: Average throughput in Mbps

case	**Slice1 average**	**Slice2**	**Slice3**	**Total**
All slices active	3.64	18.07	10.66	32.37
Slice 2 deactivated	27.99	0	24.84	52.88
Slice 1 active	53.90	0	0	53.90

6 Summary on Use Case Studies

6.1 Implemented Use Cases

This chapter summarizes the learnings and conclusions drawn from the various use cases, which the project has implemented and tested. The ambition with the implemented test cases was to cover different aspects and categories of the use cases, which were defined at the beginning of the project and which are detailed in D1.1 [1].
The covered use cases address multiple variants of V2X types, which include V2V, V2I and V2N and all relevant application classes, which are Road Safety, User Comfort and Traffic Efficiency.
Most of the implemented Use Cases were showcased in the three demo occasions during the run time of the ConVeX project, starting on a closed demo track, but also showing them in the real traffic on motorways and rural streets in Schengen and on the A9 close to Nuremberg.

6.1.1 Blind Spot Warning/Lane Change Warning

The BSW/LCW Use Case takes care about warning the driver of the host vehicle (HV) about another vehicle (RV) next to it, driving in the same direction and being in the blind zone of the HV. The Use Cases are quite similar – for the BSW it can be implemented as an advisory information, being triggered whenever this situation occurs (RV within the blind spot of the HV), for the LCW, a further input is the intend of the driver to actually change the lane, which could be taken from the indicator being activated. The evaluation of the positions is derived from the CAM.

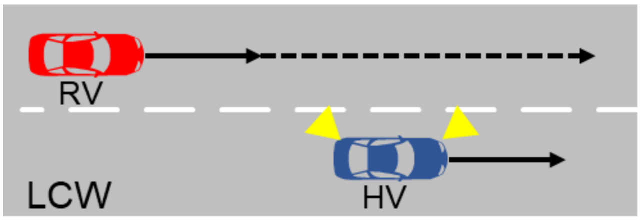

Figure 6-1: Lane Change Warning with RV approaching from behind at an adjacent lane (LCW)

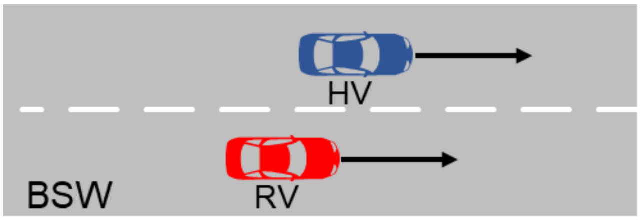

Figure 6-2: Blind Spot Warning with RV in the blind zone of the HV (BSW)

Testing of this Use Case was carried out by driving side-by-side and the RV entering and leaving the blind spot of the HV. These tests were done with different vehicle speeds (urban, motorway). The triggering was reliably working in all scenarios.
For this Use Case, there exists no specific challenge for the V2V communication part, since it operates when the communication partners are in close vicinity to each other. Also,

the cars have similar speeds, travelling in the same direction, which means very small relative speeds.
Our field-testing work has proven that today's C-V2X technology is well suited to accommodate this use case.

6.1.2 Emergency Electronic Brake Light

The Emergency Electronic Brake Light (EEBL) Use Case covers the situation, where the RV is braking hard and generates the respective message, that is broadcast to warn the vehicles in the vicinity. The receiving vehicle evaluates the relevance of this emergency braking event, and if appropriate a warning is generated for the driver in order to avoid a crash. This application is particularly useful when the driver´s line of sight vision is obstructed by other vehicles, or due to bad weather conditions (e.g., fog or heavy rain).
The EEBL event is per standard transferred by means of a DENM, and the actual determination that an Emergency braking is happening is done by algorithms in the car – the trigger towards the ITS stack is coming from the CAN interface, where a hard braking/emergency braking flag is set. The car can e.g. take a certain braking pressure as a trigger, or the negative acceleration could be evaluated to determine if it is above a defined threshold.

Figure 6-3: Emergency Electronic Brake Light

For the receiving HV, the decision for triggering the warning is based on the evaluation of the location and heading of the RV (its position and heading information is also part of the DENM) relative to the own position and trajectory of travel, i.e. means only an HV that goes into the same direction like the RV and at some point would collide with it is supposed to trigger. It is also possible to define a relevance distance – the driver of a too distant HV might not need to get the warning. This distance could also be varied taking the speed into account by calculating a time-to-collision and utilizing then a time value as threshold for the warning.
This Use Case was also implemented for a Ducati motorcycle – mainly taking the RV role, as such an implementation will increase the safety of motorcyclist by not being overlooked. The direct view to a motorcyclist is furthermore more often obstructed by a vehicle in between due to the smaller silhouette.
The Use Case was functionally tested in different setups (two cars, car and motorcycle) and with different speeds, and with and without obstructing vehicles, and could be verified as working reliably. Most tests were done in urban areas, which might also be more prone to sudden hard braking, and queues of cars, which would mean obstructed views. This means a radio-based warning would be particularly useful.
From V2V communication point of view, intermediate distances need to be covered, partly in obstructed conditions. Based on the results from section 5.1, it can be expected that the EEBL Use Case does work reliably in all relevant scenarios.

6.1.3 Intersection Movement Assist

The IMA safety application warns the driver of an HV when it is not safe to enter an intersection due to a crash possibility with RVs crossing the movement path of the HV. One can imagine many different scenario where this comes into play and is helpful, e.g. when the view into the intersection is obstructed or the driver of an HV is violating the priority, which might not be expected.
Technically, the Use Case is based on the evaluation of the content of the CAM from RVs and a comparison of their position and direction of travel with the one of the HV. If there is a collision risk, the respective warning is triggered. For the implementation, different severities of the warning where implemented: in case of a longer time to collision due to lower speeds or higher distance, the respective warning icon on the HMI was displayed in yellow, while for a more immediate danger it was shown in red accompanied with an acoustic warning.

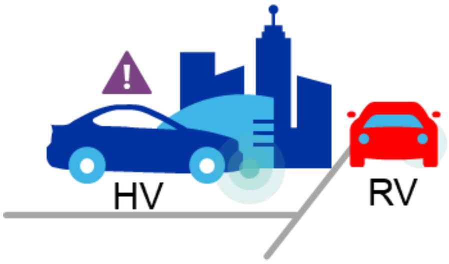

Figure 6-4: Intersection Movement Assist (here: with obstructed view)

Similar to EEBL, this Use Case was implemented and tested with cars as well as with the motorcycle and could also be proven as working reliably. After first evaluation in open conditions, it was in particular tested for obstructed view intersections.
As one can derive from the results of the Urban Range testing for different intersection types discussed in 5.1.5, this Use Case is supposed to work in all relevant scenarios, even in challenging NLOS situations, where it will be really useful and bring additional safety.

6.1.4 Left Turn Assist

In this scenario, the HV wants to turn left, and shall be warned, not to overlook oncoming traffic. This traffic might be out of sight, e.g. due to a curve, obstructing buildings, trees etc. as illustrated in Figure 6-5, or the driver is just not attentive. The localization of the RV and identifying the possibility of a collision is again based on CAM, a further needed trigger is the activation of the turn indicator at the HV: only a vehicle with the intention to turn left shall be warned. The indicator state is transferred via CAN from the car to the DP. This Use Case was also demonstrated with a motorcycle taking the role of the RV since this is a very important scenario for motorcyclists being overlooked by left turning cars, which attributes to many accidents.

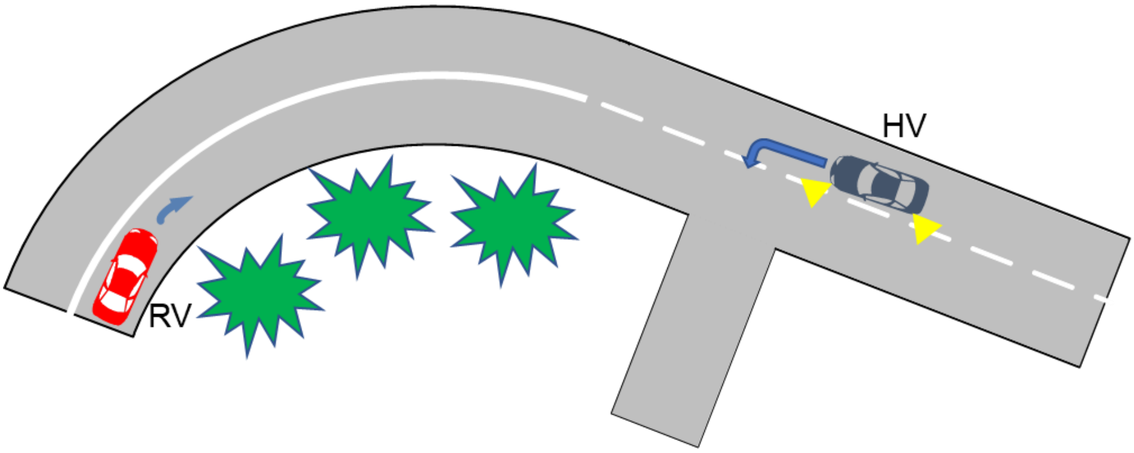

Figure 6-5: Left Turn Assist

The Use Case brings only a small challenge for the underlying communication, since only intermediate distances have to be covered, potentially with some obstruction, but the involved cars are traveling in opposite direction on the same street, facing each other. The Use Case is also expected to only trigger, if there is a real risk of a collision, it means if the RV is too far away it should not (distance again dependent on the speed of the RV)

6.1.5 Slow Stationary Vehicle Warning

This Use Case deals with scenario of a broken down (or very slowly moving) vehicle, that shall warn the oncoming traffic. Similar to EEBL, the warning is transferred via a specific DENM generated by the broken-down RV, the condition for its generation is that the car is stationary (speed=0 km/h) and the hazard warning lights are activated. Again the relevance decision is done

Figure 6-6: Slow Stationary Vehicle Warning

by the HV determining if the RV is in the direction of travel (same heading), and it is possible to configure a certain relevance distance. One can argue if the warning should be displayed as soon as the HV receives the DENM (and has checked the intersection of the position of the RV with its travel trajectory), or if there shall be an additional threshold to avoid warnings at a higher distance that might not be relevant for a driver, who e.g. will anyway leave the street at the next intersection and thus not reach the broken down vehicle. However, the additional warning might be accepted since it aims to increase safety. The implementation can also have different levels of severity for the alerting.
The communication requirements differ in line with the desired distance for the start of a warning. However also here the C-V2X Physical Layer will not be the limiting factor: for the open street conditions the LOS range tests show huge supported distances in the km range, and for obstructed views like tested in the Urban Range part all relevant distances shall be supported.
This Use Case was a new development that was originally not planned, but implemented for showing it at the Schengen Cross Border demo day – there placing the RV and HV at locations belonging to different countries, to show case that this Use Case is also working cross-borders.

6.1.6 In-Vehicle Information

“In Vehicle Information” is an Infrastructure-to-Vehicle (I2V) Use Case. C-V2X technology is used to transfer road sign information (e.g. displayed speed limits, warning sign content) in electronic form to vehicles.

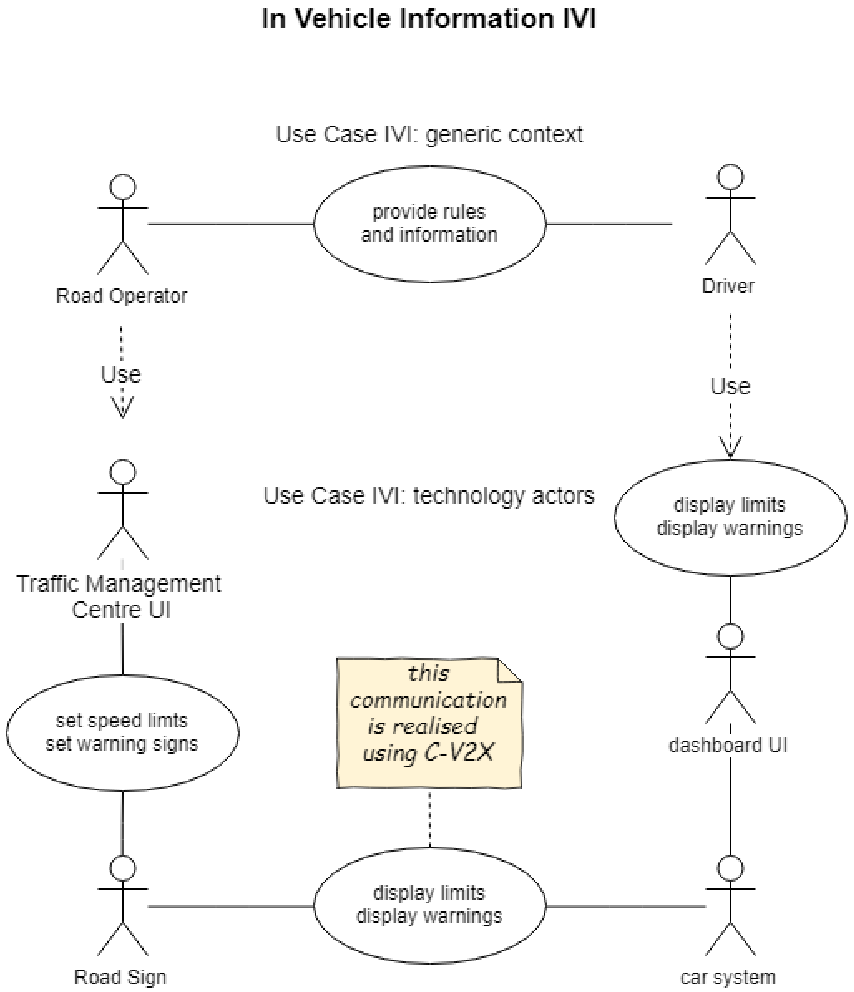

Figure 6-7: In Vehicle Information (IVI) Use Case context

For C-V2X communication the road sign information is represented in an IVI message (IVIM) defined by ETSI with data elements according to the ISO 19321 specification [20]. In the ConVeX trials, the messages are transferred using C-V2X technology. For IVI tests, the tester can select speed limits on a web-UI. This “Virtual Traffic Centre” communicates to the “virtual road sign”. The road-sign controller is physically located next to the test track (e.g. bridge over the autobahn). From there, the standard IVI message is provided by PC5 directly to the test vehicles passing by. As outlined in more details in D1.1 [1], the IVIM contains a detection zone and relevance zone coded as polygons of WGS84 longitude and latitude coordinates. The ITS SW on the OBU compares the ego position with these values and triggers the displaying of the respective sign content, when the car is within the relevance zone. The sequence of first entering the detection zone and then the relevance zone provides the possibility to only enable the signs (here the speed limit) in one direction of driving.

This concept of the definition of a relevance zone does also imply that C-V2X coverage is not a requirement for the intended location of the validity of the sign content – the information could be preloaded passing the RSU location/coverage area and will be displayed when the vehicle is reaching the relevance zone.

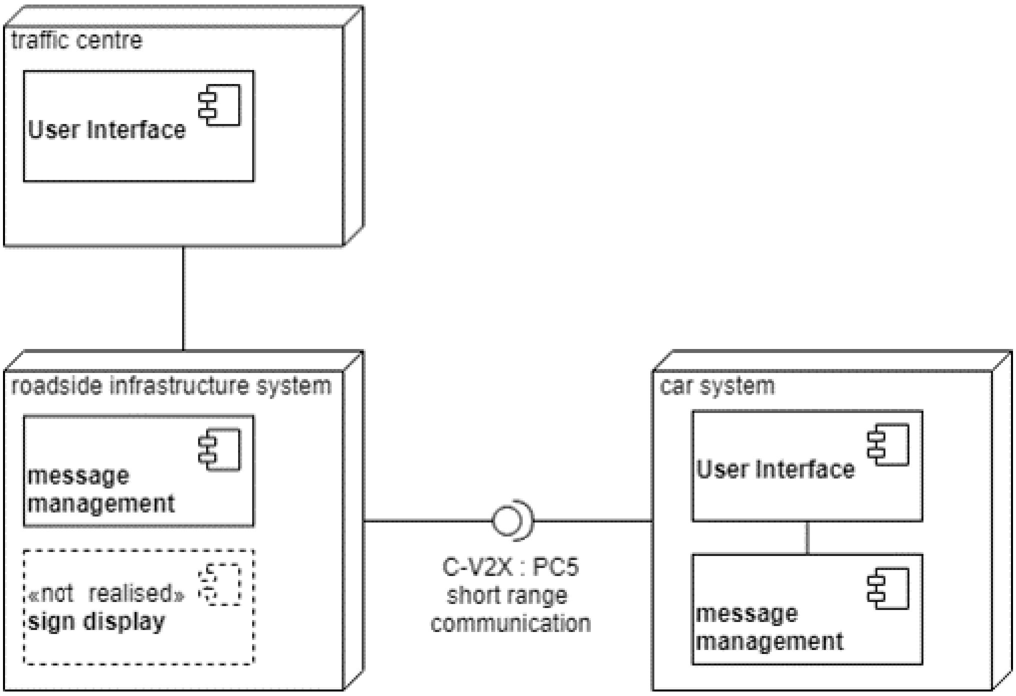

Figure 6-8: In Vehicle Information (IVI) communication setting

The different components for realization of this Use Case have been implemented end-to-end within the ConVeX project, and the IVI use case over C-V2X was showcased for the first time in Europe. The Use Case was thoroughly tested in different locations and with different vehicle speeds (urban, motorway), and was working reliably. As mentioned above, it works as soon as there is communication with the RSU at some point of the way in the intended direction of travel before the defined detection and relevance zone.

Figure 6-9: IVI Roadside System Setup
(ConVeX technical workshop and demonstration in Nuremberg)

Figure 6-10: IVI information displayed in the vehicle
(ConVeX technical workshop and demonstration in Nuremberg)

6.1.7 Roadworks Warning

Roadworks Warning (RWW) is a use case described in Cooperative Intelligent Transport Systems (C-ITS). National projects and projects of the European Commission initiated harmonization platforms, starting in Eco-AT and continuing in the C-ROADS Platform.

RWW is very similar to IVI, i.e. also here the sign content, which is the roadworks warning, is transferred via radio to the vehicle. A very relevant scenario for RWW in particular is the usage of a mobile sign, e.g. on a warning trailer. Equipping it with C-V2X technology to broadcast the warning to the upcoming traffic might avoid accidents with vehicles of inattentive drivers else not expecting nor noticing the obstacle in time. The mobile implementation would in most cases have no connectivity to a traffic center but is rather stand alone.

Figure 6-11: Roadworks Warning (RWW) – trailer examples (ConVeX Schengen demo on the right)

In contrast to IVI, for Roadworks Warning a specific DENM warning message according to ETSI EN 302 637-3 [21] is used. However, the concept is the same: again a starting location – here called event location - is defined using latitude and longitude values, plus a path, from which the intended direction can be derived, and the alert is triggered when the ITS SW on the vehicle found a match with its position and the event location, taking into account the travel direction.

For ConVeX the stand alone RSU approach was utilized: the transmission of the DENMs could be started on it, and the passing by C-V2X equipped Audi Q7 was receiving the message, and eventually showing the RWW on the dashboard starting at the appropriate location.

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Figure 6-12: Road Works Warning (RWW) on the Audi dashboard

The same testing like for IVI was carried out, in the actual RSU implementation also a combination of both messages and thus Use Cases was possible using a longer stretch of a street with the two different scenarios happening one after the other.
As mentioned earlier this was also showcased in two demo events on motorways showing the usability of these Use Cases in real world.

6.1.8 Follow-Me Information

In the Follow-Me Information (FMI) Use Case, the driver of a host vehicle (HV) gets some directional information of a selected remote vehicle (RV). He or she is then allowed to observe the current position of the RV on the HV's dashboard and can be instructed by a marker to reach that position or to follow navigation directions derived from the location information of the moving RV.
Due to security and privacy reasons, a transmitting RV will not provide a steady identifier (such as a MAC address) in CAM messages with which it could be tracked, but an additional system is required for exchanging such information and granting an HV the permission to follow a desired RV. Therefore, an additional backend component is required which provides mapping between static and dynamic user identifiers.
Testing the communication was done with two cars driving next to each other. Also, some maneuvers with changing orientation of one car and driving around the other car have been executed.
Figure 6-13 displays the test ecosystem.

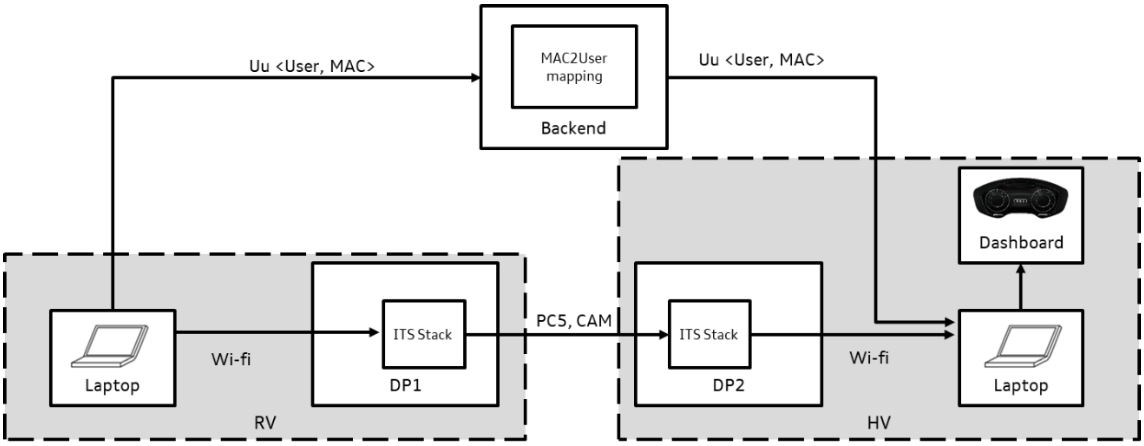

Figure 6-13: Schematic of the Follow-Me Information architecture

Figure 6-14 shows an early visualization of the use case. The FMI function in the HV gets the information about the position and compass heading of all surrounding RVs from the DP, which derives them from the received CAM. As soon as the FMI function of the HV downloads a valid MAC address from another vehicle, which allowed the sharing of its position, the HV’s display will start to show the respective information on the screen as shown in Figure 6-14.

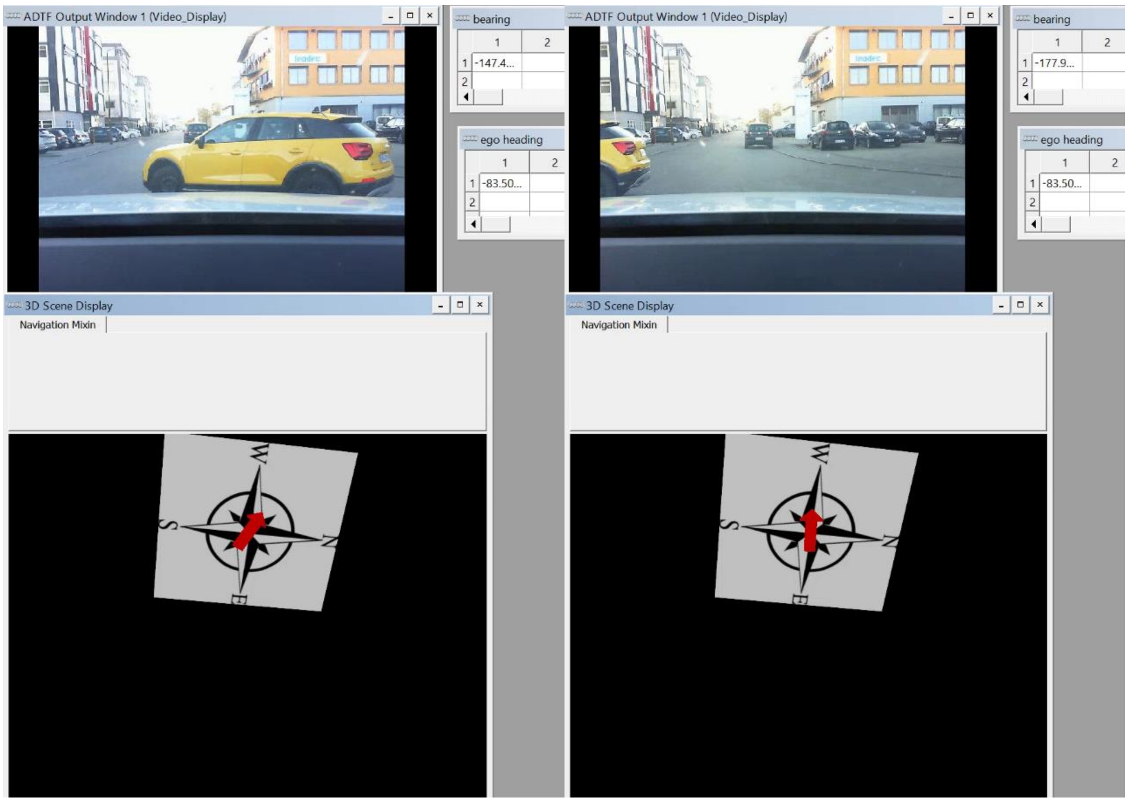

Figure 6-14: The yellow car is the RV in this scene

The FMI Use Case is an example for the extension of using ITS messages not only for basic safety, but also for some convenience functions.

Due to the decision of building the function on top of the CAM ITS messages, the recognition of the vehicle was working sufficient in distances the service was capable of receiving valid CAM data.

6.1.9 See Through

The main feature of the See Through (ST) Use Case is the provision of video streaming data via a direct link either between two vehicles or the ITS infrastructure and a vehicle. The video information could simply be used to provide the driver of a host vehicle (HV) a view from a different perspective in order to grant the driver additional visual traffic information. A more extended usage for the future could include processing of the video stream for extracting object information, e.g. other road users or any objects which may represent a hazard.

In order to transmit captured image data in real time, an event based, non-SPS flow and an IP/RTP/UDP over PC5 protocol stack was chosen. Figure 6-15displays a schematic of the test setup where a webcam installed in a Remote Vehicle (RV) was used for capturing a video the video is presented to the driver of the HV on a laptop screen or on the car’s dashboard.

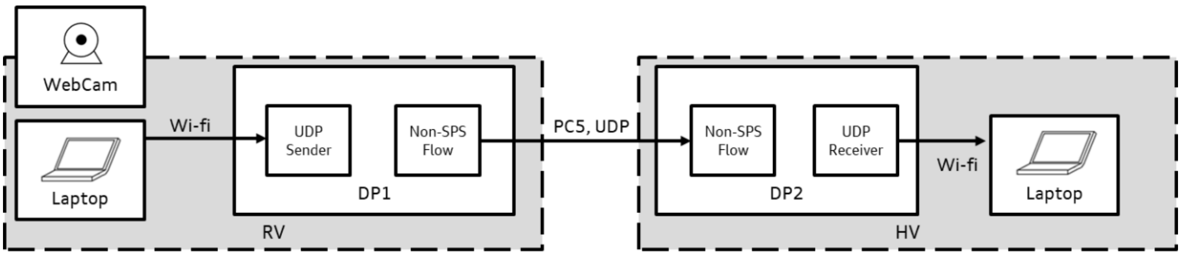

Figure 6-15: Test setup for See Through Use Case

The target of C-V2X as defined in 3GPP LTE Rel-14 is not addressing high-rate, continuous data flows, which would be needed for high quality video streams, but rather the broadcast of periodic messages, that are used for the basic safety Use Cases. A minimum periodicity of 20 ms (50 Hz) and a message size of up to 1200 bytes was taken as a design target for the FT Use Case, which translates into 480 kbps.

The goal here was anyway more to demonstrate the general possibility to use the side link direct communication for this kind of purposes.

Our results show that Rel-14 C-V2X can still fit a video stream with a resolution of 640x480 pixels.

In future 3GPP releases such as Rel-16, where 5G NR C-V2X capability will be added, dedicated high data rate connection will be possible for sharing of video images or other high throughput sensor data. This new release will take care for the needed Quality of Service requirements.

6.1.10 Range Extension

The Range Extension use case focuses on exchanging messages from vehicle to vehicle and also from the application server (AS) to vehicles. Each vehicle sends its coordinates to the AS. The AS uses these coordinates to calculate Region Of Interest (ROI) for the vehicle. Afterwards, it uses the calculated ROI to group vehicles and exchange messages between relevant vehicles.

In the following, a scenario in Figure 6-16 is assumed where a vehicle detects a slippery road via its sensors. It is equipped with both PC5-based V2V/V2I and Uu-based V2N communication capability. The vehicle transmits a DENM warning message using V2V to other vehicles in its PC5 communication range. In order to extend the PC5 communication range, the vehicle also sends the warning message using V2N communication to the AS hosted in the edge computing facility. The AS records the event in its database, and it also forwards the warning message to vehicles on the same road that are either not equipped with V2V or to vehicles out of the V2V communication range. Once a vehicle enters the slippery road, the AS sends the warning message to it. The AS would remove the warning message from its data base if it does not receive confirmation from other vehicles that the detected hazard still exists.

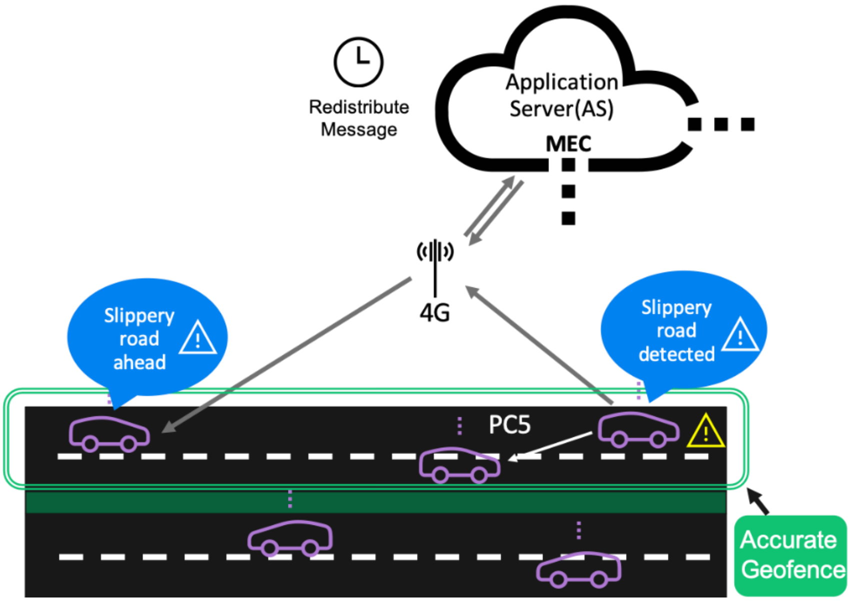

Figure 6-16 Range extension use-case diagram

6.1.10.1 Use case architecture:

Figure 6-17 depicts the components that compose the Range Extension use case. MQTT was used as a messaging protocol between vehicles and the interface to the AS. MQTT is a messaging protocol that is based on publish/subscribe transport. The underlying protocol used in MQTT is TCP.MQTT is widely used in machine type communication for its light weight and easy to use. However, MQTT was used here as an example protocol for communication. The architecture discussed here is not dependent on MQTT and it can be replaced with any protocol that fulfills the requirements.

6.1.10.1.1 MQTT vehicle client:

The vehicle is running an application with an MQTT client. Here, we assume that the vehicle has a single interface to interact with the service, which is MQTT.

6.1.10.1.2 MQTT broker:

Of the shelf open source MQTT broker hosted in the edge cloud in Greding. The broker connects to all vehicles and to the AS via the MQTT relay server.

6.1.10.1.3 Application Server:

The application server consists of multiple components. We consider AS to be any component operated by the service provider to offer the service to the client.

6.1.10.1.3.1 MQTT relay server:

The relay server is a cloud component which is responsible for translating between various protocols and interfaces. It allows two clients to communicate together even if they are not supporting the same protocol. For example, if a vehicle shares some messages with a group of vehicles and different service providers, the vehicle has to send the message to the MQTT relay server, then the relay server will translate the message to multiple protocols and formats that are accepted by other vehicles/ service providers. This ensures that the vehicle doesn’t have to send the same message multiple times on many interfaces. The relay server consists of a MQTT client that register to the MQTT broker, it also has other clients with other protocols such as HTTP, TCP and UDP. Those clients are considered as an interface to communicate with all possible clients. Where a client can be either a vehicle or a service provider.

6.1.10.1.3.2 Geocasting engine:

During the project, we developed a geo-casting service that identifies the ROI for each vehicle based on its location. The vehicle sends its current location and heading to the server. The server has pre-calculated ROI, it tries to match the vehicle to its ROI. The server replies with a message with a unique number representing the ROI and its borders coordinates. The vehicle subscribes to the topic that corresponds to the ROI (e.g. convex/out/hazard/ROI#2). Once the vehicle leaves the ROI coordinates, it unsubscribes from the old topic and requests a new ROI. If a vehicle detects a hazard, it sends a message to the relay server. The message is sent over a specific topic that all vehicles use to report hazards (e.g. convex/in/hazard). The message consists of the hazard type and its coordinates. The Geocasting engine calculates the ROI for the occurred hazard. It forwards the hazard messages on the topic corresponding to the ROI and all nearby ROIs (e.g. convex/out/hazard/ROI#1, convex/out/hazard/ROI#2 etc.….)

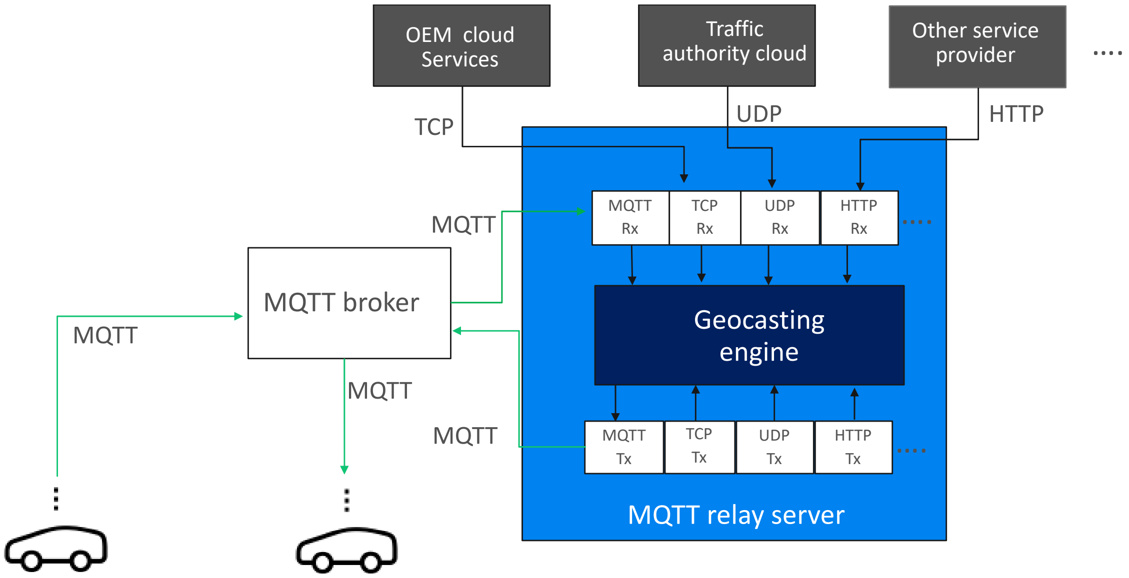

Figure 6-17: Architecture for range extension use case based on MQTT

6.1.10.2 Use-case implementation

The use-case was validated with two vehicles driving along the A9 highway. The two vehicles act as RV. They send their coordinates to the AS and receive updated ROI. A hazard warning message is sent from a virtual vehicle about slippery road. The AS calculates the ROI and logs the message to its DB. If one of the vehicles are in the ROI, it receives a hazard warning about the slippery road ahead. The other vehicle traveling in a different direction doesn't receive the warning because its ROI doesn't match the incident ROI.

6.1.11 Shock Wave Damping

The IVI Use Case described above provides a basis for many other applications. One of it is the "Speed recommendation for Shockwave damping (SWD)" Use Case. The SWD Use Case has been invented to support a more homogenous traffic flow and specifically to provide electronic speed recommendations for vehicles in the in-flow towards a traffic jam and its dangerous shock waves.

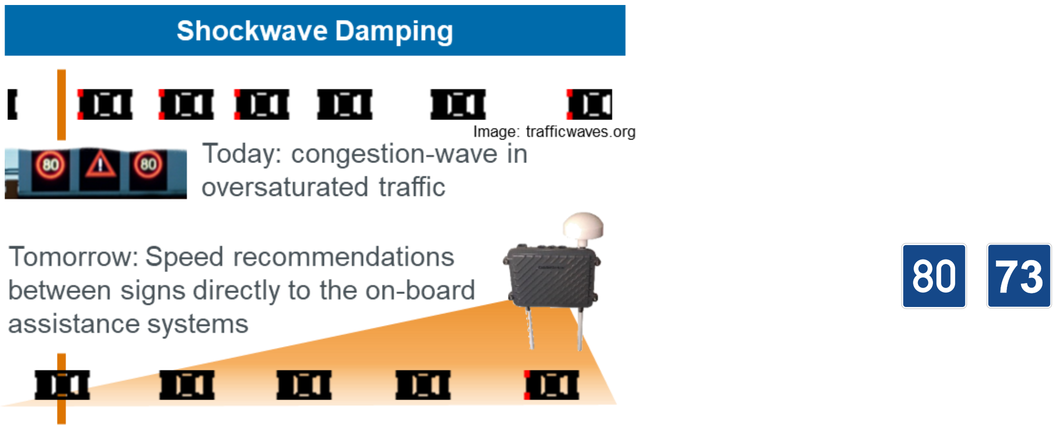

Figure 6-18: Speed recommendation for Shockwave damping (SWD)

IVI is used to provide a “recommended speed”. The target is an automated car-function which regulates the speed. Using C-V2X on PC5 to transfer IVI messages, cars (and drivers) can receive timely triggers to slow down, before a shock wave is built up. This prevents strong and sudden breaks, contributes to safety and avoids further loss of traffic flow. Apart from using the RSU to disseminate the speed recommendations, it can also be used as a powerful detector of speed information from all the cars in the vicinity, simply utilizing the information inside the CAMs received (assuming these cars will be equipped with C-V2X in the future). The RSUs would feedback aggregated speed information back to the traffic center, where sophisticated algorithms would analyze the data, detect changes in the traffic flow, and calculate the speed recommendations to avoid the shock waves.

Within the ConVeX project, parts of this future looking Use Case were implemented and also theoretically addressed with simulations. On the practical side, the following was realized:

To show the aspect of the RSU as a probe of the traffic, a piece of SW was implemented, that is evaluating received CAM in a way, that the speed of a car driving inside a certain defined area is averaged. When the car leaves this area, the result is sent over to a virtual traffic center via the normal LTE network using the Uu interface. According to the settings of the traffic center, the speed value would e.g. be rounded down to the next 10km/h step and reduced by 10 km/h, and the calculated value goes back to the RSU, which is using it as the speed recommendation value in an IVI, that it starts transmitting, valid for a stretch of the street further downstream. In this demo setup, the car, whose speed was detected from its CAMs, is then also getting the recommendation based on its own previous speed (e.g. average speed of the car: 73 km/h, rounded down to 70 km/h and reduced by 10 km/h => speed recommendation: 60 km/h). The recommendation value of 60 km/h is displayed to the driver on the dashboard of the car.

Figure 6-19: Speed recommendation for SWD (here combined with Roadworks Warning)

Apart from this practical implementation of the complete chain of elements, also simulative work was done:

In order to understand the achievable gains in terms of traffic homogenization, a preliminary simulation for this use case was carried out for different penetration rates of Connected Vehicles (CV’s). A 2-lane highway stretch of 500 m long is created using SUMO and vehicles are inserted at an initial flow rate of 1800 vehicles/hour. A shockwave is created by explicitly slowing down one vehicle in each lane for a brief amount of time (refer Figure 6-20). Due to this, a shockwave is created and propagates backwards. Each

CV in the shockwave transmits CAMs to a RSU (since the stretch of the road is 500 m, a single RSU is deemed sufficient to transmit and receive all messages). The message includes its current velocity and position. The message is transmitted at a frequency of 10 Hz. The local shockwave speed (taken by replacing the macroscopic quantities in the shockwave speed equation[1]), u_{loc}, can be determined by taking the position and speed information of any two consecutive CV's (minimum) as

$$u_{loc} = \frac{{}^{v_{n-1}}/_{d_{n-1}} - {}^{v_n}/_{d_n}}{{}^{1}/_{d_{n-1}} - {}^{1}/_{d_n}}$$

Equation 1: Shockwave Speed (Knopp V.L. (2017).Introduction to Traffic Flow Theory)

where, u_{loc} is the localized shockwave speed, v_{n-1}, d_{n-1} is the speed and headway of the following CV and $v_n, d_n$is the speed and headway of the leading CV. Once the local shockwave speed is determined, this speed is transmitted to the incoming CVs by the RSU, which in-turn reduce their speed by at least u_{loc} to prevent the shockwave from propagating any further. This speed recommendation doesn't ensure that the shockwave will be immediately damped, as vehicles closer to the shockwave might not get enough time to adjust to this recommendation. However, it does ensure that the inflow of vehicles into the shockwave is reduced.

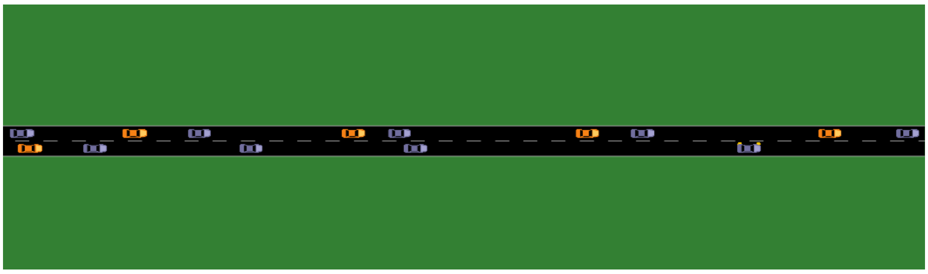

Figure 6-20: Two lane highway represented in SUMO-GUI with conventional vehicles (in grey) and CVs (in orange)

For the purposes of the simulation, a few assumptions were drawn, which are as follows:

1. The shockwave is generated by slowing down a vehicle at a predefined time and location
2. The consecutive CVs that send CAMs to the RSU (to calculate the u_{loc}) are assumed and known to be a part of the shockwave
3. There is already a mechanism in place to detect and identify the source of the shockwave.
4. The reaction times of vehicles is kept in the range of 0.5 – 0.8 seconds, i.e., the vehicle adapts to the new speed in 0.5 – 0.8 seconds after the message is successfully decoded from the RSU

The effects of various penetration rates of CVs can be seen in the Space-Time figures (refer to Figure 6-21). A typical shockwave on a space-time graph can be seen in Figure 6-21 a). It is characterized by incoherent speed transitions arising due to human behavior, and a propagation speed also arising due to the slow reaction times of human drivers. With sufficient inflow of vehicles, the shockwave can continue for a long time. For the inflow used in the simulation the shockwave is short and is dissipated in about 85 seconds. Not much of a difference can be seen with the 33% IVI penetration case (refer to Figure 6-21 b) with the only difference being that a number of small stop-and-go waves being created. The few vehicles that do receive the speed advisory from the RSU adapt to it and hence this breakup in shockwave can be seen. In the 66% case (refer to Figure 6-21 c) this effect can be seen more prominently and the shockwave as a whole is damped in about 55 seconds (a gain of 35.29%). As the penetration rate of CVs reaches 100% (refer to Figure 6-21 d)), the shockwave is not only damped much earlier (in about 35 seconds – a gain of 58.82%) but the shockwave is also transmitted downstream rather than upstream

In the Figure 6-21 a) and b), there are vehicles at position 0 m with zero speeds (seen in the red and yellow region in the lower side of the plots). This is not a secondary shockwave and is due to the high density of vehicles that the simulator is inserting at this point. The vehicles start at very small headways and adjust their speeds accordingly. A high density of vehicles is needed to successfully simulate the generation of a shockwave.

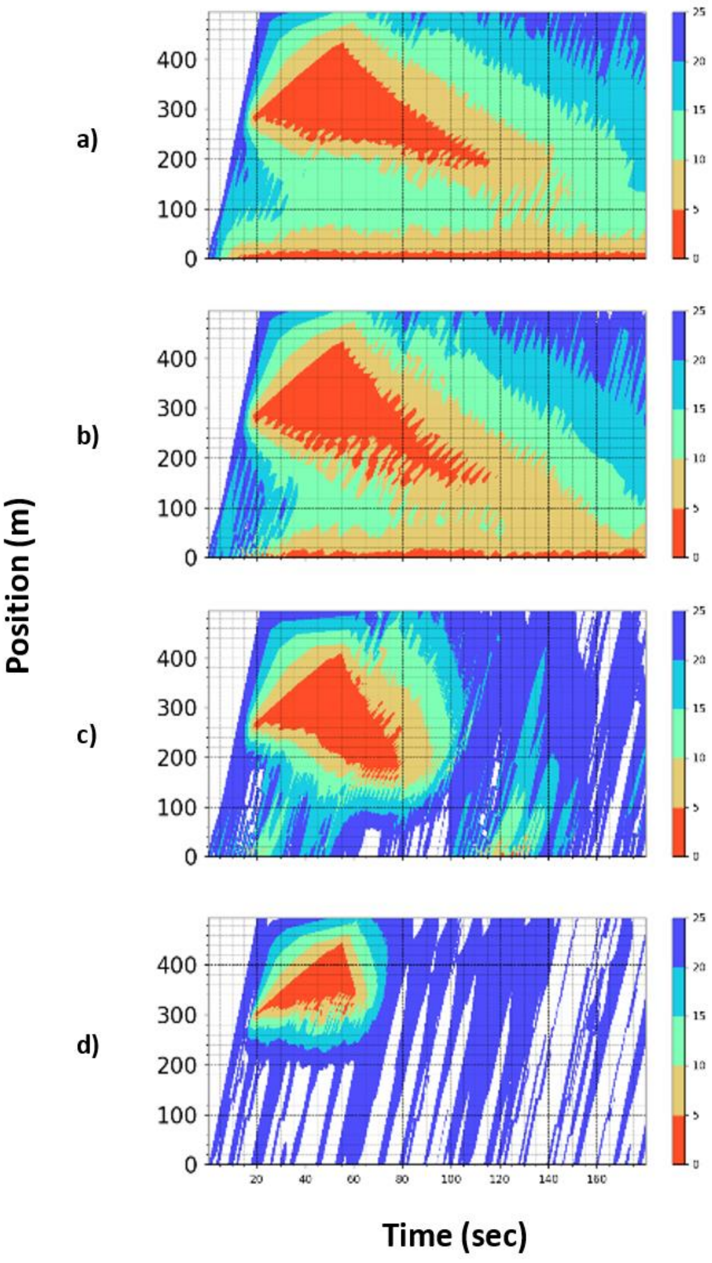

Figure 6-21: Space-time diagrams for different penetration rates of CVs: a) 0%, b) 33%, c) 66% and d) 100%. The color bar represents the speeds of vehicles in mps. The red region indicates the shockwave travelling upstream (against the flow of traffic)

6.2 Dropped Use Cases

Some of the initially defined ConVeX use cases where not implemented and verified during the project. From the beginning it was not meant to have all the use cases covered, but to have a range of use cases that cover the different aspects, which the project investigated. In some cases, the additional effort to realize the dropped use case, was not justified by the additional results that were expected from the realization and testing.

In other cases, some of the expected results was determined without the implementation of the specific use case. For example, Do Not Pass Warning (DNPW) realizes sharing of specific information in a relevant zone, which was covered by similar use cases as well (e.g. Left Turn Assist (LTA) or Slow Stationary Vehicle Warning (SSVW). Most relevant for the use case was however the determination of achieved communication ranges and behavior at high speed, which were covered by dedicated lab and specifically field measurements. The DNPW Use Case is furthermore logistically challenging since three cars need to be coordinated and the testing has to happen on a close test track to keep the execution safe.

Below the use cases are listed which were not implemented for one of the above reasons and thus have not been specifically described in this document:

- Vulnerable Road User
- Do Not Pass Warning
- Cloud Based Sensor Sharing
- Network Availability Prediction

7 Summary on Simulation Studies

In communication system design, simulations are necessary to analyse and optimize algorithms & procedures prior to their full scale deployment. In this context, both link and system level simulators were deployed in order to evaluate the performance of C-V2X. The link level simulation is basically a software implementation of one or multiple links between UEs, with a channel model to reflect the actual transmission of waveforms generated. System level simulations, on the other hand, are used to evaluate the performance of a larger network comprising of multiple UEs and eNBs by abstracting the PHY aspects by means of SNIR-BLER mapping curves.

7.1 Link Level Simulation

The complete PHY layer processing chain for C-V2X (refer Figure) has been implemented in Python3 using native numpy and scipy modules. The developed code is performance matched and calibrated with the Matlab's LTE system toolbox that supports Rel.14 C-V2X. For benchmarking and comparison, IEEE 802.11p PHY layer pipeline (refer) was used which is available in the WLAN system toolbox of Matlab.

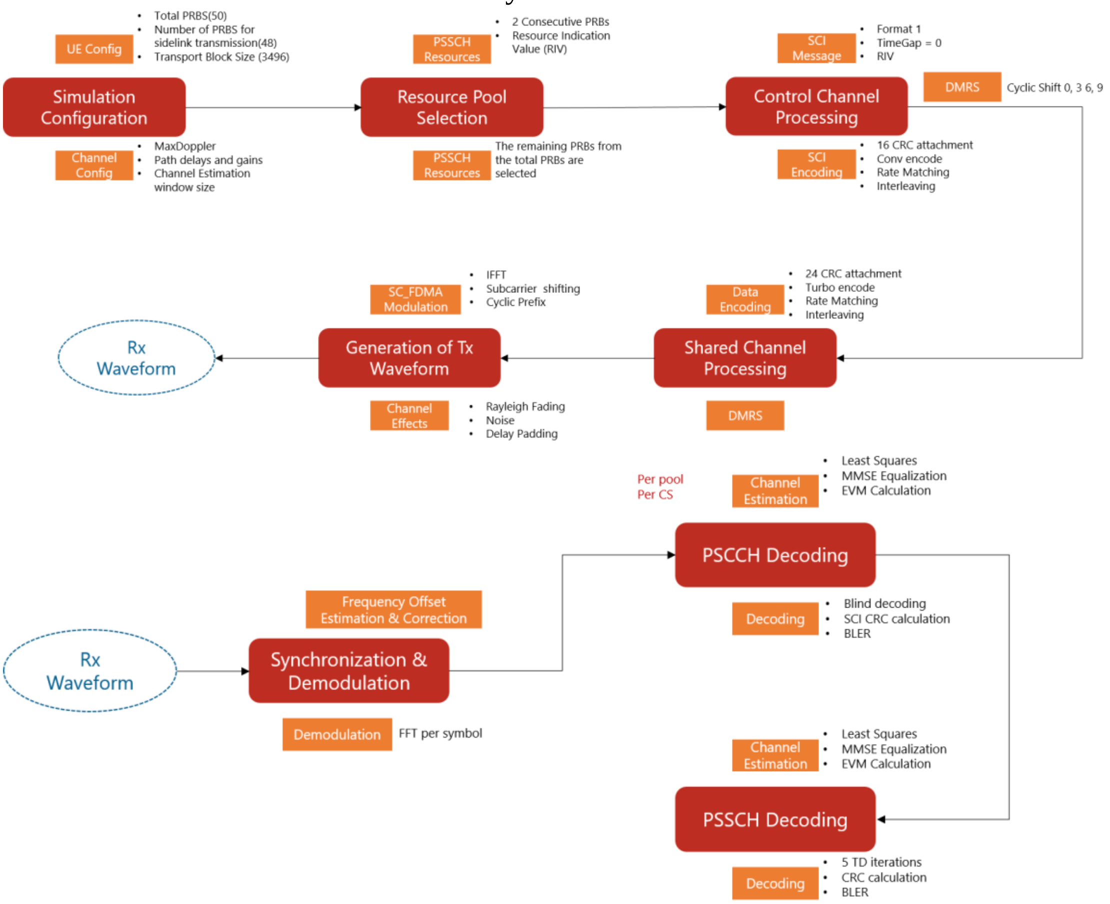

Figure 7.-1: PHY Pipeline for C-V2X

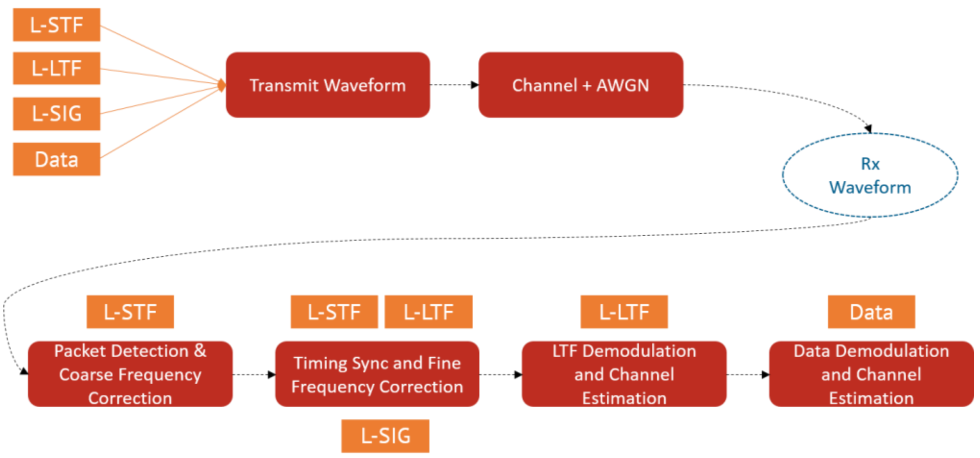

Figure 7-2: PHY Pipeline for 802.11p (ITS-G5)

Different channel models were considered for performance evaluation. They are

1. AWGN Channel
2. ITU Channel Models (Vehicular A (ITU-VA), Vehicular B (ITU-VB) and Extended Vehicular A (ITU-EVA)
3. DSRC Tiger team channel models (Rural LOS, Urban Approaching LOS, Urban NLOS, Highway LOS and Highway NLOS)

Figure 7-3 shows the BLER performance over AWGN channel for ITS-G5 and C-V2X respectively for all the supported MCS schemes. It can be seen that C-V2X shows a performance gain between 3 - 8 dB over ITS-G5. Such a high gain can be attributed to more efficient turbo encoding scheme and the use of one blind retransmission in C-V2X. The retransmission effect is more pronounced for higher coding rates than the lower coding rates. For example, for MCS 0, there is almost a 3 dB gain whereas for MCS 10 the gain is 6 dB. Similarly, for the case of 16QAM, MCS 11 has a gain of 3 dB whereas MCS 20 has gain of almost 8 dB. This is also the reason behind the big gap between QPSK and 16QAM schemes in C-V2X.

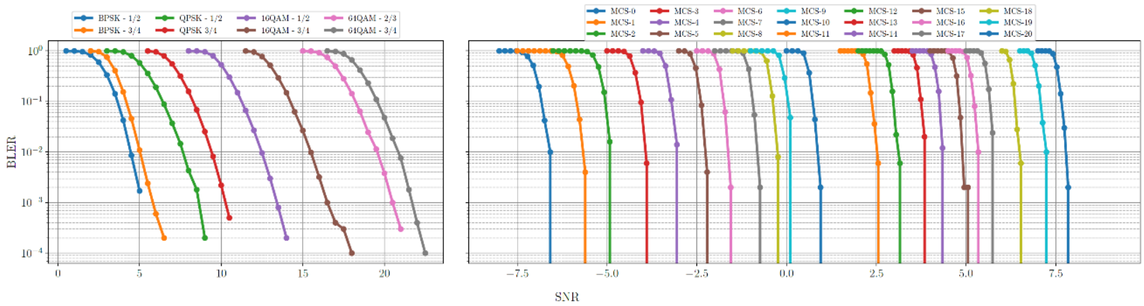

Figure 7-3: AWGN Performance comparison for ITS-G5 and C-V2X

Coming to fading channels, for the sake of a neutral performance comparison, no retransmissions were assumed for C-V2X. The considered use cases deal mostly in traffic safety and hence require robust MCS schemes instead of high data rate schemes. Therefore, the performance comparison is limited to QPSK schemes with coding rates ½ and ¾ as outlined in Figure 7-4. In general, it can be seen that C-V2X outperforms ITS-G5 by 2-4 dB margin with the exception of Model 5 (Urban Approaching LOS) where the performance of both the technologies is more or less the same. This better performance can be attributed to the better channel estimation in C-V2X which uses evenly spaced DMRS symbols compared to ITS-G5 that only uses the preamble. Hence, it can be said that C-V2X is better equipped to handle faster channel variations which is the case with C-V2X.

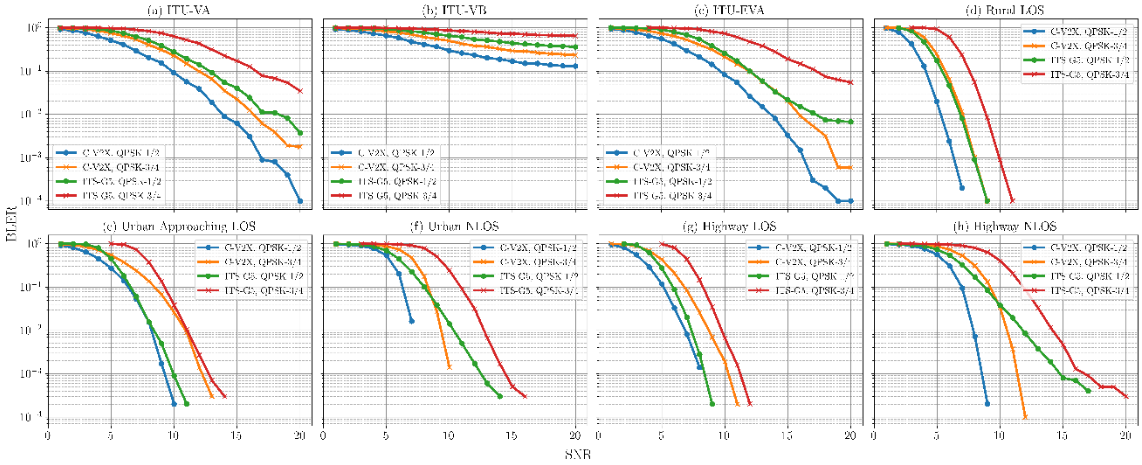

Figure 7-4: Performance Comparison for Fading Channels

7.2 System Level Simulation

System-level simulations are generally based on multi-cell and multi-user scenarios., taking into account the system relevant functionalities like network layout, channel model, scheduling and characteristics of eNBs and a mobile UEs. The field trials performed by the ConVeX project have used mode 4. However, capacity evaluation was not part of the field trials. For the evaluation by system simulation, we have chosen mode 3, in order to also include an evaluation of this mode in the project.

In this context, a 6-lane highway scenario is considered with 2 cells in line with 3GPP specifications. Cars are randomly deployed with varying inter-vehicle distances ranging from 5-100 m. Depending upon the number of vehicles and the message frequency, the total data volume is calculated that is used to derive the required MCS to support all the UEs. For this purpose, the SINR-BLER curves for the AWGN and EVA channel models (with and without retransmissions) were used from the link level simulations. For each scheduled sidelink transmission, a random interfering UE is assumed which can be either from the same cell or the adjacent cell. The PRR for the current scheduled transmission is calculated by considering the signal, noise and interference powers. Finally, the PRR's for all the scheduled transmissions are averaged.

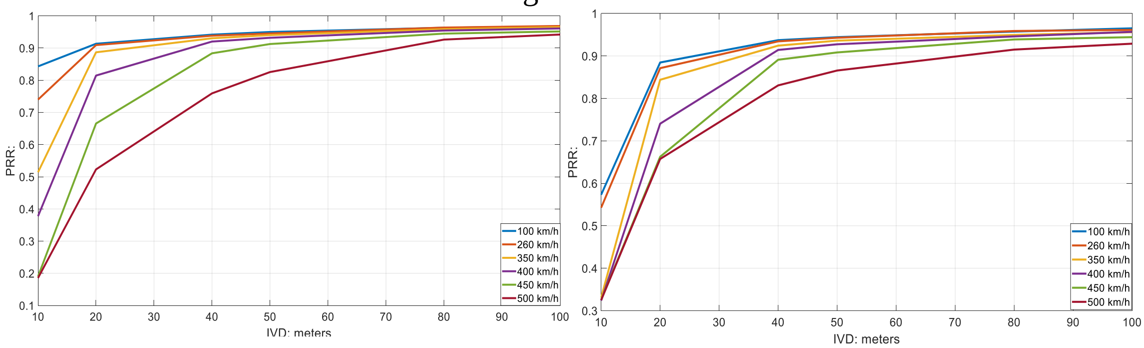

Figure 7-5: PRR for EVA Channel without and with one blind retransmission for different vehicle speeds

For a message rate of 10 Hz, the PRR is above the 90% target for all Inter-Vehicle-Distances IVD above 40m and UE speeds up to 400 km/h when the MCS is optimally chosen. For 500 km/h this is only the case for IVD above 80 m, however, given the high speed the breaking distance does also require such high IVD.

With a single retransmission, the load is naturally doubled and accordingly less robust MCS is used. There are hardly any simulation scenarios where retransmissions can lift the PRR above the target of 90%. However, some aspects of the link and system simulation scenario are expected to contribute to that the retransmissions do not harvest the full diversity gain potential. At high speeds retransmissions do increase the PRR by 10 - 15%, however, still only at an unacceptably low level.

The conclusions seen from the system level analysis on LTE-V2X sidelink “mode 3” is that it suffers from performance issues in addition to a number of added complex requirements and business considerations. As such, the preferred technology for direct communications is LTE-V2X sidelink “mode 4” which does not require the network for the sake of resource control. This underlines that the field trials were executed with right mode, and in the meantime also the industry moved into this direction for the commercialization of C-V2X.
NOTE: A extensive set of simulations can be found in deliverable D3.2 [4]

8 Concluding remarks

The ConVeX Project was showing the power and potential of the newly defined and implemented LTE Rel. 14 C-V2X technology, and each of the partner companies will consider individually how to apply the project results to the respective portfolio.

There still exists demand for further research work beyond the scope of the ConVeX project around C-V2X technology. Potential future research could address the following important topics:

- Large scale trials of C-ITS safety applications with many vehicles involved: Such trial scenario will become practically feasible when C-V2X enabled mobile phones will become available which could be installed in the test vehicles with small effort and low cost. In such trial, spectrum capacity and load issues could be evaluated.
- Installation of roadside ITS infrastructure with full area-wide coverage, e.g. in the A9 digital test field. Deployment and evaluation of new innovative ITS services, including traffic flow control services such recommended speed based on automatically sensed real traffic conditions.
- Development, integration and demonstration of new innovative C-ITS services, covering all important service categories, i.e. improved road safety, improved traffic efficiency, driver convenience, also taking account service which become feasible due to the upcoming deployment of 5G technology
- Demonstration and performance evaluation of upcoming new features of 5G C-V2X 3GPP Rel-16 technology
- Demonstration of the merits of C-V2X technology for autonomous driving: Integration of C-V2X technology into self-driving vehicles as complement to in-build sensor technology. Development of software modules that integrate sensor data and ITS information received via C-V2X