5GMOBIX

5G for cooperative & connected automated MOBIlity on X-border corridors

D3.2

Report vehicle development and adaptation for 5G enabled CCAM use cases

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ABBREVIATIONS

Abbreviation	Definition
AD	Autonomous/Automated Driving
ADAS	Advanced Driver Assistance System
AI	Artificial Intelligence
AV	Automated Vehicle
CV	Connected Vehicle
CAV	Connected and Automated Vehicle
CBC	Cross Border Corridor
CCAM	Cooperative, Connected and Automated Mobility
CAM	Cooperative Awareness Message
CN	China
CoCA	Cooperative Collision Avoidance
CPM	Collective Perception Message
C-ITS	Cellular Intelligent Transport System
C-V2X	Cellular Vehicle to Everything
DE	Germany
DTS	Decoding Time Stamp
EC	European Commission
ES	Spain
EU	European Union
EV	Electronic Vehicle
FI	Finland
FR	France
GA	General Assembly
GDPR	General Data Protection Regulation

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GR	Greece
HD	High Definition
HMCU	Hybrid Modular Communication Unit
HW	Hardware
ITS	Intelligent Transport System
Km	Kilometre
KPI	Key Performance Indicator
KR	Korea
LDM	Local Dynamic Map
LiDAR	Light Detection and Ranging
LTE	Long-Term Evolution
MCM	Manoeuvre Coordination Message
MCS	Manoeuvre Coordination Service
MEC	Multi-access/Mobile Edge Computing
MIMO	Multiple-Input and Multiple-Output
mmWave	Millimetre Wave
MNO	Mobile Network Operator
MSG	Message
NSA	Non-Standalone Architecture
NL	Netherlands
OBU	On Board Unit
OEM	Original Equipment Manufacturer
PLMN	Public Land Mobile Network
PT	Portugal
PTS	Presentation Time Stamp
QoS	Quality of Service

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RAN	Radio Access Network
RSI	Roadside infrastructure
RSU	Roadside Unit
SA	Standalone Architecture
SAE	Society of Automotive Engineers
SGI	Serving Gateway Interface
SW	Software
SWIS	See-What-I-See
TC	Technology Centre
TR	Turkey
TS	Trial Site
UCC	User Story Category
UE	User Equipment
US	User Story
VM	Virtual Machine
VRU	Vulnerable Road User
V2I	Vehicle to Infrastructure
V2X	Vehicle to Everything
VR	Virtual Reality
VW	Volkswagen
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WP	Work Package
WPL	Work Package Leader
X-border	Cross-border
3GPP	The 3rd Generation Partnership Project

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5G NR	5G New Radio

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EXECUTIVE SUMMARY

This deliverable aims to give a detailed view about what is installed or modified in vehicles' sensors and software and the adaptation of the OBU to the 5G technology, in the context of the 5G-MOBIX Project. This document completes the technical descriptions done in D2.4 (1), adding descriptions of the works carried out in vehicles and OBUs to meet the UCCs requirements.

First, it presents a summary about the common updates and installations made in all vehicles and OBUs. It also provides a deployment plan describing how those activities have been distributed over time. Following, a current integration status of vehicles and OBUs is described, sorted by CBC and TS. Next, a review of the SAE levels applied to the project, determining the maximum level for each vehicle related to the capabilities and UCCs of 5G-MOBIX.

The main body of the deliverable is divided in three main parts. The first two sections are dedicated to vehicle integration in the CBCs, with descriptions of the upgrades and installations done in ES-PT CBC and GR-TR CBC. The third section describes the vehicle and 5G OBU integration for each TS. Each of these sections is divided in: Sensors & devices integration, Automated driving functions development, OBU integration, collaboration between sites and a sub-section with descriptions of the unitary testing done at the time of writing. Sub-section 1.4– Structure of the document, provides a deeper insight into each of the sections mentioned.

Last section is dedicated to conclusions obtained from the information that also compounds this document.

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1. INTRODUCTION

1.1. About 5G-MOBIX

5G-MOBIX aims to showcase the added value of 5G technology for advanced Cooperative, Connected and Automated Mobility (CCAM) use cases and validate the viability of the technology to bring automated driving to the next level of vehicle automation (SAE L4 and above). To do this, 5G-MOBIX will demonstrate the potential of different 5G features on real European roads and highways and create and use sustainable business models to develop 5G corridors. 5G-MOBIX will also utilize and upgrade existing key assets (infrastructure, vehicles, components) and ensure the smooth operation and co-existence of 5G within a heterogeneous environment comprised of multiple incumbent technologies such as ITS-G5 and C-V2X.

5G-MOBIX will execute CCAM trials along cross-border (x-border) and urban corridors using 5G core technological innovations to qualify the 5G infrastructure and evaluate its benefits in the CCAM context. The Project will also define deployment scenarios and identify and respond to standardisation and spectrum gaps.

5G-MOBIX has first defined critical scenarios needing advanced connectivity provided by 5G, and the required features to enable some advanced CCAM use cases. The matching of these advanced CCAM use cases and the expected benefits of 5G will be tested during trials on 5G corridors in different EU countries as well as in Turkey, China and Korea.

The trials will also allow 5G-MOBIX to conduct evaluations and impact assessments and to define business impacts and cost/benefit analysis. As a result of these evaluations and international consultations with the public and industry stakeholders, 5G-MOBIX will identify new business opportunities for the 5G enabled CCAM and propose recommendations and options for its deployment.

Through its findings on technical requirements and operational conditions, 5G-MOBIX is expected to actively contribute to standardisation and spectrum allocation activities.

1.2. Purpose of the deliverable

The present document, D3.2 "Vehicle adaptation for CCAM use cases", is the outcome of T3.2 with the same name. This deliverable describes in detail, the SW and HW modules developed in the project's deployment phase, the updates performed in the vehicles and infrastructure as well as the integration process. These upgrades are necessary to support the implementation of the UCCs defined in the Project and described in Deliverable D2.1 (2). The CBC descriptions will include a summary of issues and solutions that appear during the integration and development period and if any of these issues are resolved with the collaboration of the TS.

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1.3. Intended audience

The deliverable D3.2 – Vehicle adaptation for CCAM use cases is a public deliverable and it is addressed to any interested reader. However, it specifically aims to provide 5G-MOBIX consortium members with an extensive set of data explaining how the development of different devices and their integration in the vehicles were made.

1.4. Structure of the document

The D3.2 document is structured as follows:

Section 1, Introduction, briefly describes the 5G-MOBIX project and the purpose of this document together with its intended audience.
Section 2, Vehicle integration roadmap & SAE LEVEL, provides an overview of the required updates in vehicles (software, sensors and OBU) and a general deployment plan stating when each hardware and software component should be developed and integrated. This section shows the current vehicle and OBU integration status in each CBC and TS and, finally, presents a SAE level review where the AD level used by each CAV in the 5G-MOBIX project can be consulted.
Section 3, Vehicle integration of ES-PT CBC, describes the vehicles integration process for ES-PT CBC, the different TS contributions to this CBC and the results from early unitary test.
Section 4, Vehicle integration of GR-TR CBC, describes the vehicle integration process for GR-TR CBC, the TS contributions to this CBC and the results from early unitary test.
Section 5, TS vehicle integration, describes the vehicles integration process for each TS and, as in the previous sections, the results of the unit tests done.
Section 6 presents the **conclusions**.

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2. VEHICLE INTEGRATION ROAD MAP & SAE LEVEL

The Vehicles used in the trials are one of the most relevant technical component of 5G-MOBIX. To address the specific purpose of the project they had to be updated, i.e., new sensors and devices must be installed, new software must be created and new OBUs with 5G connectivity must be developed to support the User Stories defined in Deliverable D2.1 (2).

The most common changes or updates done in vehicles and their planning are presented, as a summary, in the following two sub-sections.

2.1. Needed upgrades

the most common updates to develop the UCCs are grouped in the following points:

- **In vehicle equipment**: the vehicles in CBC and TS were updated with new sensors and hardware for AD, new cameras for remote driving and new devices for multimedia services. All this equipment was described in D2.4 (1) and the installation process is presented in the current deliverable.
- **5G OBUs**: at the beginning of the project, the OBUs of the vehicles did not have 5G connectivity. Thus, they had to be updated with the new 5G modems, or in some cases, new OBUs with 5G connectivity had to be created.
- **Software components**: to support the new in-vehicle equipment, some new software has been developed. This new software adapts the current version of many components in the CBC and TS to support all new functionalities to carry out the UCs.

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2.2. Deployment plan

In D3.1 (3), a 5-Phase Rollout Timeline was presented, where each of them is in charge of developing different activities. Figure 1 presents a summary of the 5-Phase plan for T3.2. In Phase 1, all the processes to be developed in Phase 2 were defined. This deliverable D3.2 is one of the outcomes of Phase 2, where the Cross-Border Corridors and the Trial Sites must integrate all equipment, hardware and software in their vehicles. Further, the results of Phase 2 will be tested and verified in the following Phases.

It is necessary to mention that the overall timeline has been affected by different delays in the context of this phase 2, mostly caused by the unavailability of 5G chipsets. This situation led to substantial delays in developments and integrations, which were subsequently also transferred to testing and the start of trials. these delays and their implications are detailed in WP4 deliverables.

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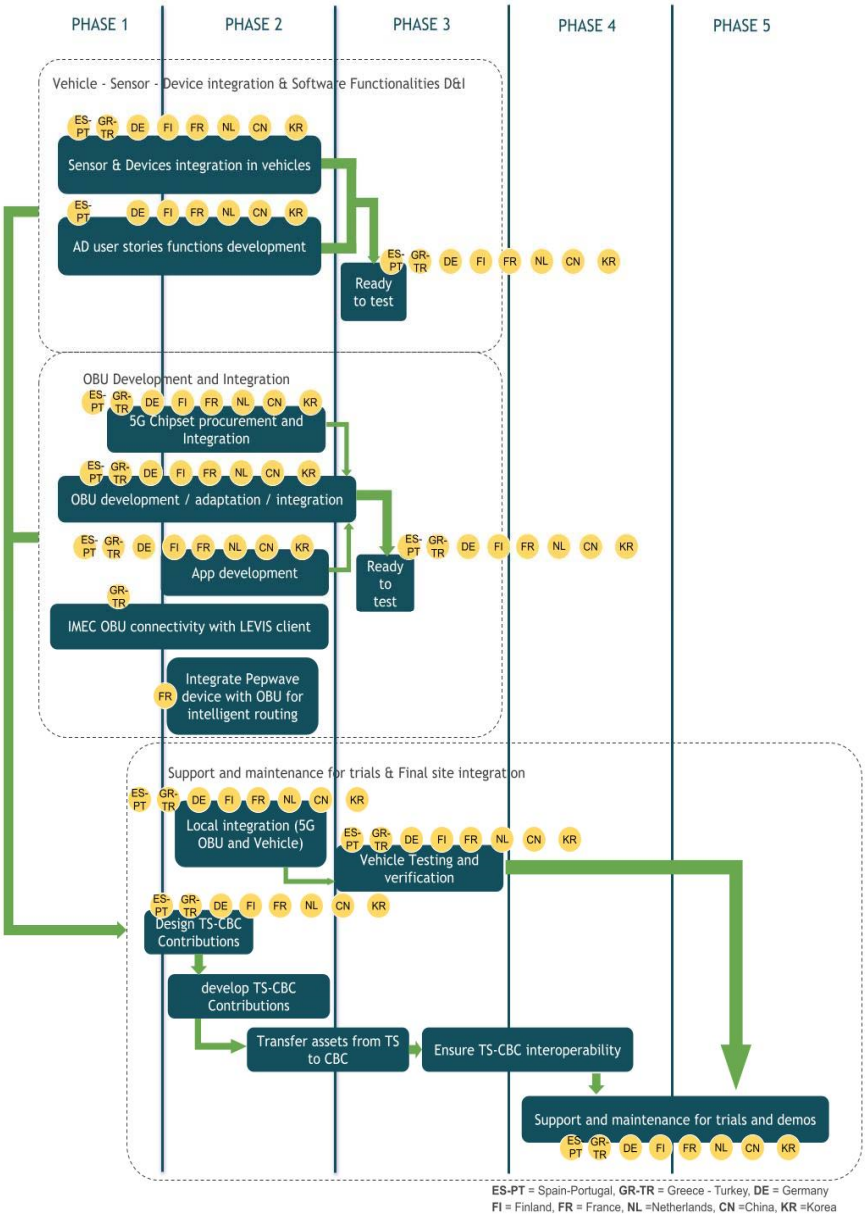

Figure 1: Overall Picture of the 5-Phase Rollout Plan for Vehicle Adaptation

2.3. Current integration status

At the time of this deliverable, the current integration status of the vehicles (sensors and other devices) and the OBUs is described in the following table:

Table 1: Vehicle & OBU integration current status

CBC/TS	Ready	Pending	Status & remarks / characteristics
ES-PT	3 Citroën C4 1 Volkswagen Golf 1 Bus ALSA 1 Shuttle 1 PT connected vehicle	-	All vehicles have finalized its sensor and OBUs integration. All vehicles have already been tested in local and cross-border areas (just with one network, since inter-plmn was not fully available) and are ready for executing the cross-border trials.
	10 OBUs	-	Integrated. Fully ready, under continuous testing.
GR-TR	2 Ford F-MAX	-	Integrated. Fully ready, under continuous testing.
	3 OBUs	-	Fully ready, integrated and verified.
DE	2 Vehicles / 2 Cohda Wireless OBUs (PC5) 2 Valeo Peiker Vulcano 2.0 (5G)	-	Use cases have been tested using Quectel modems and Valeo Peiker to provide 5G Uu interface access and Cohda Wireless MK6c to provide access to the PC5 interface. The OBUs are mounted and ready for the trials.
FI	1 CAV & 1 CV / 2 OBUs	-	Vehicles are ready - 2 multi-SIM OBU NSA available M26, integration to vehicle M27, OBU upgraded to SA M32
FR	1 CAV & 2 CVs / 5 OBUs		Vehicles and OBUs are completely integrated and ready.

NL	3 CAV. & 1 CV. / 5 OBUs	1 OBUs	1 OBU (remote driving – mm-wave) is developed and tested in lab, plan for testing Q2-2022.
CN	1 Vehicles	1 OBU	The vehicles will be integrated with the OBUs in May 2021
KR	2 Vehicles / 1 OBUs	1 OBU	The tethering use case is ready (OBU and Vehicle test in Oct'21) OBU for remote control use case will be ready in Mar'21.
Total	**23 Vehicles / 30 OBUs**	**0 Vehicles / 3 OBUs**	

In ES-PT there are more OBUs than connected vehicles. The reason for this is that apart from the 6 OBUs developed for participating in the User Stories as connected vehicles, there are some other ones developed for producing extra network traffic. The objective with these extra OBUs is to simulate a more realistic scenario, where not only the trial vehicles are using the resources of an entire network, but there are many other vehicles stressing the network with data traffic.

2.4. SAE level review

In 5G-MOBIX project, several vehicles with different SAE levels participate in the CCAM User Stories. Table 2 presents a summary of these vehicles, describing their capabilities (in terms of 5G features and automotive functionalities) and the way they are used in the project. In this table, only connected and autonomous vehicles are included.

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Table 2: SAE level summary by site

CBC/TS	Type of vehicle	Max. SAE level	SAE level used	Vehicle capabilities	Application in 5G-MOBIX
ES-PT	1 Shuttle EV Bus	4	4	• Autonomous urban driving L4 (longitudinal and lateral control) • 360º Object detection (pedestrian, vehicles, bicycles). • Route following (HD map information). • Automated emergency braking. • Collision detection (Prediction of possible collision). • Remote Driving. • ITS communications.	• UCC#1 -> User Story: Automated shuttle in cross-border settings (Cooperative automated operation): The vehicle uses jointly L4 functionalities and ITS communications for following its route autonomously and protect other users in the road. • UCC#4 -> User Story: Automated shuttle in cross-border settings (Remote control): The vehicle uses its L4 functionalities for following its route autonomously while conditions are met. When these conditions are broken, the vehicle is remotely operated.
	1 Citroën C4-Picasso	4	3-4	• Autonomous urban driving L4 (longitudinal and lateral control) • Highway chauffeur L4 (vehicle following, automated overtaking, highway entry, highway exit and fall-back). • Route following (HD map information).	• UCC#1 -> User Story: Complex manoeuvres in cross-border settings (Lane merge & Automated overtaking): The vehicle makes use of the L4 highway chauffeur functionalities and the ITS communications for driving autonomously and cooperate with other vehicles in the road.

				• Automated emergency braking. • Collision detection (Prediction of possible collision). • ITS communications. • Sensors recording & upload.	• UCC#3 -> User Story: Complex manoeuvres in cross-border settings (HD maps): The vehicle uses ITS communications for receiving notifications about the state of the road, and records and uploads its sensor data for processing a new map in the cloud. In this case, autonomous functionalities are just L3, since the vehicle needs to be manually controlled when conditions are not met (map outdated).
	1 Citroën C4-Picasso	0	0	• ITS communications.	• UCC#1 -> User Story: Complex manoeuvres in cross-border settings (Lane merge & Automated overtaking): The vehicle, being manually driven, uses ITS communications for providing other vehicles and infrastructure with information about it (position, heading, speed, etc), so that other vehicles can adapt its intentions of manoeuvre.
	1 Volkswagen Golf	4	4	• Autonomous urban driving L4 (longitudinal and lateral control) • Highway chauffeur L4 (vehicle following, automated overtaking, highway entry, highway exit and fall-back). • Route following (HD map information). • Automated emergency braking.	• UCC#1 -> User Story: Complex manoeuvres in cross-border settings (Lane merge & Automated overtaking): The vehicle makes use of the L4 highway chauffeur functionalities and the ITS communications for driving autonomously and cooperate with other vehicles in the road.

				• Collision detection (Prediction of possible collision). • ITS communications. • HD map download & installation.	• UCC#3 -> User Story: Complex manoeuvres in cross-border settings (HD maps): The vehicle uses ITS communications for receiving notifications about the state of the road, and is able to download and install a new version of the HD map, for keep always driving autonomously.
	1 ALSA bus	0	0	• ITS communications. • Sensors recording & upload. • High quality multimedia content download. • Video surveillance in real-time.	• UCC#3 -> User Story: Complex manoeuvres in cross-border settings (HD maps): The vehicle uses ITS communications for receiving notifications about the state of the road, and records and uploads its sensor data for processing a new map in the cloud. In this case, the vehicle is always manually driven. • UCC#5 -> User Story: Public transport with HD media services and video surveillance: The vehicle in this case has the capability of providing its passengers with access to high quality multimedia content. Furthermore, operators from the public transport company can monitor the inside and outside of the vehicle in real-time from their offices.
	1 PT Connected Vehicle	1	0	• Regular Renault Megane vehicle with limited driving assistance capabilities.	• UCC#1 -> User Story: Complex manoeuvres in cross-border settings (Lane merge & Automated overtaking): The vehicle sends information regarding its own position and

				• Lane centring and adaptive cruise control. • Pedestrian detection system with collision avoidance/automated emergency braking system.	dynamics, receiving the same type of information from the other vehicles and displaying it on a mobile app to the driver. • UCC#3 -> User Story: Complex manoeuvres in cross-border settings (HD maps): As in the previous User Story, the vehicle sends information regarding its own position and dynamics, receiving the same type of information from the other vehicles plus the road event notification and the HD-Map update from the ITS Centre. All this information is presented to the driver in the mobile app.
GR-TR	2 FORD-MAX	4	4	• Autonomous Urban Driving L4 • Autonomous Highway Platooning (Longitudinal and lateral control, no need to human intervention) • Automated emergency braking • Path following • Collision detection (Prediction of possible collision). • Lane departure warning • See through • CO_2 emissions and Cargo identification (NFC reader), front ultrasonic sensor • Front RADAR, camera • Precise GNSS positioning with RTK (Less than 1 meter)	• User Story: Platooning with See What I See Application settings: In this scenario vehicle will use its Autonomous Highway Platooning , see through, lane departure warning functions. • User Story: Autonomous Truck Routing in Border Crossing: Autonomous Urban Driving L4 vehicle. In this scenario, LIDAR sensors) will be placed around of the facility. When vehicle reach the facility, application will be launched and sensor data placed on the facility will be sent to cloud. Meanwhile vehicle will send its precise GNSS position and speed information also to cloud. Cloud will fuse this data and create a path

					information that will be dynamic and change according to environment. After that path info will be delivered to vehicle. Vehicle will follow this path autonomously without any human intervention. • User Story: Assisted -zero-touch- truck border-crossing: In this use case CO_2 emissions, Cargo identification (NFC reader), and front ultrasonic sensors will be used.
DE	1 Volkswagen Passat (Valeo)	4	1	• 360º object detection (four fisheye cameras) • 360º surround view generation • LIDAR (Velodyne32/64) and/or Valeo SCALA/SCALA2	• User Story: EDM-enabled Extended Sensors with surround view generation. o On-board cameras video transmission to a remote vehicle to enhance its perception. • RADARs used for reference purposes • User Story: eRSU-assisted platooning o Platoon follower functionality o Exchange of necessary platoon messages with platoon leader in order to follow it.
	1 Volkswagen Tiguan (TUB)	4	1	– Autonomous driving L4 (longitudinal and lateral control). SAE capabilities not used due to licenses needed in public road from DE-TS – 360º surround view generation – HD Cameras and LIDAR – Lane detection	– User Story: eRSU-assisted platooning o Platoon leader functionality o Reception of infrastructure information directly via PC_5 or through the MEC broker via Uu – User Story: EDM-enabled extended sensors with SW generation.

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					o 4x cameras video stream reception from remote vehicle and Surround View generation
	1 Toyota Prius (Vicomtech)	4	1	• Autonomous driving L4 (longitudinal and lateral control). • 360º object detection (HD cameras and LIDAR) • Driver monitoring (attention, gaze direction, drowsiness) • Collision detection (estimation of collision probability) • 360º surround view generation • Lane departure warning • Free space detection	• User Story: EDM-enabled Extended Sensors with surround view generation. • Object detection and risk estimation (collision probability) to assess the need for extended sensors. 360º surround view generation from a remote vehicle's cameras to enhance the perception obtained with on-board sensors.
FI	1 Renault Twizy (Ava, SENSIBLE4)	4	4	• Autonomous urban driving L4 • HD mapping and localisation • Object detection • Path following • HD Cameras and LiDAR • Remote monitoring and control • Road legal in mixed traffic, up to 40km/h.	• User Story: Remote driving functionality with increased capability provided by 5G networks in a redundant (multi-PLMN) network environment.
	1 Ford Focus (AALTO)	1	1	• Machine vision grade camera installation for forward view • Vehicle communication interface for data collection (CAN bus) • On-board computer • RTK capable GPS	• User Story: Extended Sensors with redundant edge processing. HD video streamed from vehicle to MECs hosting HD maps application. Evaluate the reliability and performance of networking and edge computing.

				• ADAS research platform	
FR	Renault ZOE (VEDECOM)	4	4	• Autonomous urban driving L4 (longitudinal and lateral control). • High-level systems for planning and supervision • LiDARs, RADARs • Object detection • Path following • 360° perception • Front and back cameras • RTK capable GPS • Vehicle communication interface (CAN) • On board computer	• User story: infrastructure-assisted advanced driving (lane change manoeuvre and speed adaptation): The infrastructure assesses the possible collision risk of the CAV with another connected or basic vehicle. If the risk is real, MEC sends MCM to the CAV to change its lane. The AV, the Renault ZOE, upon the reception of the MCM, it will autonomously change the lane, following the trajectory guidance included in the MCM.
	Renault SCENIC	1	1	• Object detection • Vehicle communication interface (CAN) • On board computer	• User story: infrastructure-assisted advanced driving (lane change manoeuvre and speed adaptation): The infrastructure assesses the possible collision risk of the CAV with another connected (SCENIC) or basic vehicle. If the risk is real, MEC sends MCM to the CAV (ZOE) to change its lane.
NL	1 VW Touareg (Martti)	4	4	• Automated Valet Parking L4. • Green light optimal speed adaptation. • Object detection • Path following • Collision detection (Prediction of possible collision)	• User Story: Cooperative Collision Avoidance: the vehicle detects collisions based on status data from other vehicles and in-vehicle sensors. The vehicle selects and follows a trajectory based on obstacles detected, initial desired path and data from other vehicles and infrastructure.

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	1 Toyota Prius PHV	4	3-4	• Rebalancing / Valet Parking L4 • Object detection (HD cameras and LIDAR) • Path following • Collision detection • Remote driving	• User Story: using remote driving functionality to take over control of the vehicle over 5G network. Using detection for enhancing remote driving. Since remotely driving, L3 is correct level to be used. • User Story: 2nd vehicle in Cooperative Collision Avoidance User Story (with Martti vehicle), using object detection.
	1 Toyota Prius	4	3-4	• Automated Valet Parking L4 • Object detection • Path following • Collision detection • Remote driving	• User Story: using remote driving functionality to take over control of the vehicle over 5G network. Using detection for enhancing remote driving. Since remotely driving, L3 is correct level to be used.
CN	SDIA	4	4	• Autonomous driving L4 • Collision detection • Path planning • Platoon • Object detection • Remote driving • HD mapping and localisation	• User Story: Cloud-assisted advanced driving: the roadside unit, the remote control centre and the cloud server will monitor and control the autonomous vehicles in real time, to perform tests of vehicles Internet-connected applications, safely and efficiently. • User Story: Cloud-assisted platooning: The autonomous driving vehicle fleet communicates with each other through LTE-V at the start. Among them, the leading vehicle includes the platoon control unit (PCU), which coordinates the vehicles in the fleet to ensure a certain safe

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					distance and to drive in a platoon. The leading vehicle communicates with the control centre deployed in a cloud server through V2N to obtain the test scheme and the global path planning. Then it provides the basic planning for the rear vehicle through V2V communication (including chasing, continuous running, acceleration, deceleration, obstacle avoidance, overall acceleration, and deceleration, etc.). The following vehicle also has a certain perception and planning decision-making ability. Besides, LTE-V communication can be replaced by DSRC technology, and comparison between these two methods will be implemented.
KR	Renault XM3 (Arkana)	4	4	• Autonomous urban driving L4 • 360° surround view monitoring • Front, Left, Right and Rear-view monitoring • Lane Departure Warning • Front Collision Warning • Parking Assist • Rear Collision Warning • Short/Long Range Blind Spot Detection • Remote monitoring and control	• User Story: 360° surround view monitoring and Front, Left, Right and Rear-view monitoring system of the remote vehicle is implemented to enhance the perception obtained with on-board sensors such as RADAR, camera, and ultrasonic sensors. ADAS systems such as lane departure warning, front collision warning, parking assist, rear collision warning and blind spot detection system are also implemented to improve vehicle safety level for remote driving.

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As shown in the table above, in some cases the level of automation used by each vehicle is lower than the maximum SAE level declared. In ES-PT different kind of vehicles have been selected for performing trials: autonomous connected vehicles, manual connected vehicles, and also legacy vehicles with any type of connectivity or automation. The reason for this variety is to build more realistic scenarios of the near future where different kind of vehicles will need to coexist. Furthermore, some L4 autonomous vehicles are in some cases used as L3 vehicles when needing to be manually driven for specific User Story scenarios.

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3. VEHICLE INTEGRATION OF ES-PT CBC

The ES-PT test and trials will take place using different vehicles depending on the User Stories. The two Citroen C4, Volkswagen Golf and the CTAG Shuttle are vehicles which have autonomous driving capabilities whereas the PT vehicle and the ALSA Bus do not have those functionalities. Details about equipment installed in those vehicles are available in section 3.1 and details of the developed software functions can be found in section 0. Furthermore, the 5G OBU is integrated by CTAG in almost all vehicles besides the equipment aforementioned, to carry out the User Stories. The PT vehicle is the only one which has a different OBU provider, developed by IT, to be used in the User Stories it participates. Table below provides an overview of vehicle related equipment installed for the ES-PT trial, while details regarding their design, development and testing are provided in the following sub-sections.

Table 3: Vehicle equipment and driving functions utilized in the ES-PT CBC

User Story	Scenario	Vehicles	Sensors	Driving functions
Complex manoeuvres in cross-border settings	Lane merge & Automated overtaking	Citroen C4 VW Golf	LASER, LiDAR, Cameras, GPS	• Highway chauffeur L4 (vehicle following, automated overtaking, highway entry, highway exit and fall-back). • Route following (HD map information). • Automated emergency braking. • Collision detection (Prediction of possible collision).
		PT Connected Vehicle	GPS	• Manual driving
Complex manoeuvres in	HD maps	Citroen C4 VW Golf	LASER, LiDAR, Cameras, GPS	• Highway chauffeur L4 (vehicle following, automated overtaking, highway entry,

cross-border settings				highway exit and fall-back). • Route following (HD map information). • Automated emergency braking. • Collision detection (Prediction of possible collision). • Sensors recording & upload.
		ALSA Bus	LiDAR, Cameras, GPS	• Sensors recording & upload.
		PT Vehicle	GPS	• Manual driving
Automated shuttle remote driving across borders	Cooperative automated operation	CTAG Shuttle	LASER, LiDAR, Cameras and GPS	• Autonomous urban driving L4 (longitudinal and lateral control) • 360º Object detection (pedestrian, vehicles, bicycles). • Route following (HD map information). • Automated emergency braking. • Collision detection (Prediction of possible collision).

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	Remote control	CTAG Shuttle	LASER, LiDAR, Cameras and GPS	• Autonomous urban driving L4 (longitudinal and lateral control) • 360º Object detection (pedestrian, vehicles, bicycles). • Route following (HD map information). • Automated emergency braking. • Collision detection (Prediction of possible collision). • Remote Driving.
Public transport with HD media services and video surveillance	-	ALSA Bus	GPS, 4K cameras, individual infotainment displays	• High quality multimedia content download. • Video surveillance in real-time.

3.1. Sensors & devices integration

It was necessary to integrate several sensors and devices in the vehicles as described in D2.4 (1). The following table summarizes all this equipment per vehicle.

Table 4: ES-PT CBC in vehicle equipment

Equipment	Vehicle Type	Units	Model	Car position	Horizontal field of view	Vertical field of view	Range
2D LASER	CTAG shuttle	3	Sick	Front and lateral	180º	0º	10m
	Citroen C4	2	Valeo ScaLa	Front and rear bumper	145º	3,2º (4 layers)	200m
	Volkswagen Golf	2	Valeo ScaLa	Front and rear bumper	145º	3,2º (4 layers)	200m
LiDAR	Alsa Bus	1	Velodyne	Front	180º	30º	6m-100m
	CTAG shuttle	2	Velodyne	Roof	360º	30º	6m-100m
	Citroen C4	1	Velodyne	Roof	360º	30º	6m-100m
	Volkswagen Golf	1	Velodyne	Roof	360º	30º	6m-100m
Cameras	Alsa Bus	1	IDS	Front	60º	-	60m (car) 40 m (ped.)
		2	Laiatech 4k	Roof (inside)	108º	-	-
	CTAG shuttle	1	FLIR	Front	60º	-	60m (car) 40 m (ped.)
		4	ELP	Windshield (Front, Rear, Left, Right)	120º	-	-

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	Citroen C4	1	Mobileye	Windshield	30°	-	150m (car) 40 m (ped.)
		1	IDS	Front	60°	-	60m (car) 40 m (ped.)
	Volkswagen Golf	1	Mobileye	Windshield	30°	-	150m (car) 40 m (ped.)
		1	Basler	Front	60°	-	60m (car) 40 m (ped.)
GPS	Alsa Bus	1	Trimble	Roof	-	-	-
	CTAG shuttle	1	Trimble	Trunk	-	-	-
	Citroen C4	1	Trimble	Trunk	-	-	-
	Volkswagen Golf	1	Trimble	Trunk	-	-	-
	PT Vehicle	1	Trimble	Roof	-	-	-
Tablets	Alsa Bus	60	ONdROAD a33-7a	One per seat	-	-	-
	PT Vehicle	1	-	Dashboard-mounted			
Router 5G	Alsa Bus	1	Xacom Compal 5G	Trunk	-	-	-

In each vehicle, the devices listed above were installed in different places, depending on the shape of the vehicle, device features and what was desired to measure. The installation process for each vehicle is described below.

3.1.1. Citroën C4 and Volkswagen Golf

The autonomous vehicles are equipped with several sensors needed for perceiving the surroundings. In this case, both vehicle models are equipped with almost the same sensor models.

The main source of information for detecting nearby vehicles is the LiDAR sensor, which provides the ADAS systems and functions with this information about other vehicles' presence. LiDAR Velodyne VLP16 has been integrated on the roof of the vehicle providing 360º coverage of the surrounding objects within a 100-meter radius, which is the maximum distance specified by the manufacturer for this sensor. Positioning this Velodyne sensor on the roof of the vehicle allows taking advantage of the complete vertical field of view of the sensor (+-15º) since it is placed high enough to avoid occlusions by the car's own chassis. The coupling component for attaching this LiDAR sensor to the rooftop was designed by CTAG.

For detecting vehicles ahead and behind with a higher distance range, LASER sensors are used. Valeo Scala-1s are placed on the front and rear bumper of the car. They have a 145º horizontal field of view, so they only detect objects ahead of and behind the vehicle within the mentioned region of coverage. Its distance range is much higher (allegedly 200 meters, around 130 meters for cars in practice), so that it enables earlier detections in a high-speed scenario (typically highways). Their integration in the car involved cutting and modifying the bumper pieces.

Accurate positioning is almost compulsory in autonomous vehicles. For this reason a GPS Trimble sensor is integrated on the trunk of the car. This GPS model has a maximum positioning accuracy of 0.25 m + 1 ppm horizontal and 0.5 m + 1 ppm vertical. The maximum operating limit for vehicle speed is 515 m/s and 18000 m in terms of altitude. The antenna connected to this GPS is located on the roof of the vehicle, avoiding signal loss or attenuation due to vehicle chassis.

Finally, with the intention of implementing different algorithms for improving autonomous driving such as road lines, object and traffic sign detection and recognition, different cameras are used. Each vehicle is equipped with two cameras, which are integrated in the top of the front windshield, inside the wipers cleaning zone, so that their view is always clean from rain or dust. Moreover, from this position, the sensors can get the maximum vision angle. Both prototypes are equipped with a Mobileye camera, and with an IDS camera (for Citroën) or a Basler camera (for Volkswagen), each of them implementing different algorithms.

Below, Figure 2 and Figure 3 show the vehicles with an overview of the sensors installed.

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Figure 2: Overview of the Citroen C4 Picasso with all sensors

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Figure 3: Overview of Volkswagen Golf vehicle with all sensors / components

3.1.2. CTAG Shuttle

The dimensions of this prototype are wider than for the two aforementioned cars, so the sensors distribution is also notoriously different. An overview of this vehicle is shown in Figure 4.

Two LiDAR Velodyne VLP-16s were placed on the rooftop of the shuttle, one on the front end, and the other on the back end. Both sensors were tilted 10º downward in their intended directions of detection (front and rear, respectively). The reason for angle tilt is to take better advantage of the sensing characteristics of the sensor. Due to the reduced speed of the vehicle, Velodyne's range of detection was considered as enough. No Scalas (longer range) were considered necessary. For the placement of both LiDARs Velodyne, the chassis of the shuttle was modified with pieces designed on purpose.

Regarding the camera sensors, in this vehicle several ones have been installed. Centred in the top of the front windshield, to get a good view angle of the road, a Flir camera model was placed to detect objects, traffic signs and lines.

Figure 4: Overview of the Shuttle EV Bus

Apart from this camera used for autonomous driving functionalities, four other cameras have been integrated around the vehicle to enable the remote driving functionality by providing the remote operator with a clear view of the vehicle surroundings. Figure 5 shows the camera model used for the Remote control scenario.

Figure 5: Remote Driving cameras model

The cameras have a 1920x1080 resolution at 30 FPS. The cameras were selected to be compatible with the Jetson Xavier NX board. This hardware that performs the encoding of the H.264 UDP video based on the M-JPEG flow of each individual camera. The development team initial expectation was that different models of cameras would be required for manoeuvring and for normal driving. After testing different models of cameras they realized that a single model with a Field of View of 120º is enough for providing a surrounding view of more than 180º in the front view of the vehicle.

3 cameras will be placed in the front and lateral parts of the shuttle and a fourth one in the rear part of the vehicle. This fourth camera will project a reverse stream view in a virtual mirror located in the VR model in which the real-time streams are blended into the scene.

A board needs to be used in order to encode real time video. The following matrix was analysed for Nvidia boards:

Video Encoding Capabilities of NVIDIA boards					
BOARD	FAMILY	H.264	H.264	H.265	H.265
		4K @ 30 (YUV 4:2:0)	1080 @ 30 (YUV 4:2:0)	4K @ 30 (YUV 4:2:0)	1080 @ 30 (YUV 4:2:0)
Jetson Nano	Maxwell	YES	YES	YES	YES
		1x	4x	1x	4x
Jetson TX2	Pascal	YES	YES	YES	YES
		3x	14x	3x	8x
Jetson Xavier NX	**Volta**	**YES**	**YES**	**YES**	**YES**
		2x	**14x**	**2x**	**14x**
Jetson Xavier	Volta	YES	YES	YES	YES
		8x	30x	8x	32x

Figure 6: Nvidia small boards comparison

Even though Jetson Nano was capable of encoding 4 simultaneous full-HD streams at 30 FPS, a very low latency is required for the scenario and almost 100% of the resources were used when testing with this board. Jetson Xavier NX offered up to 14 simultaneous streams at this resolution leaving some room for extra processing, decoding and VPN client management in the connection. Due to this, the final selection was the Xavier NX board.

Figure 7: Jetson Xavier NX Board

A Jetson Xavier NX is connected to both the OBU (to get 5G Connectivity) and to the fourth cameras. The connection to the four cameras is done through USB 3.0 using the four available ports. The ethernet port is connected to the CTAG HMCU to get a 5G SGI IP. A portable battery module is used to provide power supply to this board. This allows an autonomy of about 4 hours or unlimited if connected to an AC supply plug in the shuttle. This board provides the system with hardware accelerating video encoding using the Nvidia H.264 encoder built in. It is accessible via gstreamer interfaces and provides four independent and

simultaneous threads of encoding at resolutions up to 2K using this codec, leaving some free resources in the execution.

3.1.3. ALSA Bus

The ALSA public transport bus was equipped with different sensors and devices for each User Story where it participates.

On the one hand, for being used in the HD maps scenario, this bus was equipped with the necessary sensors for sensing the road and build a new HD map update. These sensors (common to the ones installed in autonomous vehicles) are a LiDAR Velodyne VLP16 for detecting objects on the road, that has been integrated on the front of the vehicle to allow a larger vision angle covering a range of 50 meters (but only with 180º of horizontal coverage). A Trimble GPS unit was installed on the roof of the bus for recording the trajectory followed with centimetre level position accuracy (0.25 m + 1 ppm horizontal and 0.5 m + 1 ppm vertical). An IDS camera is integrated at the centre of the front windshield, which will record the video of the vehicle's front view to extract lines, signals and other objects from it in post-processing.

On the other hand, for the Quality of Service scenarios (4K surveillance and Multimedia services for passengers) the bus was equipped with two 4K cameras placed in the inside of the bus. One of them oriented to the front windshield, so that it can monitor the outside of the vehicle, and the other one oriented to the inside so that it can see the passengers' area. The only use of these two cameras is to stream its video recording to the ALSA control centre in real-time. Moreover, a set of 60 individual infotainment displays have been integrated in the bus (one per seat) so that all the passengers can interact with them and enjoy the high quality multimedia content that the User Story provides.

The other equipment specified in **Table 4** has been integrated in one of the luggage compartments available on the bus. Integration of several components can be seen in the following Figure 8.

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Figure 8: ALSA Bus integration Overview

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3.1.4. PT Connected Vehicle

The PT connected vehicle is involved in most of the User Stories of the ES-PT CBC, not only enhancing interoperability within the corridor with all other vehicles and infrastructure, but also increasing the load on the 5G network and creating a more realistic traffic situation (most of the vehicle traffic expected under operation in 5G networks will be from connected vehicles rather than from autonomous ones) continuously throughout the User Stories. In addition, this vehicle carries a OBU different from the ones on the rest of the vehicles in the corridor. It was developed by the project member (IT) and allows validating results and comparing data. This is especially important in regards to the evaluation of the network performance in each of the User Stories and locations.

The PT CV is a regular passenger car, with no automated driving functionalities besides the current SAE level 1 capabilities of most commercial vehicles. It is solely retrofitted with a 5G OBU, a Time Server based on GNSS signal and a GNSS receiver for localization purposes. This way, it can send and receive information regarding its own position and dynamics, which is used in the lane merging and overtaking scenarios under the "Complex Manoeuvres in Cross-Border Settings" User Story.

Figure 9: PT Connected Vehicle.

In addition, the PT CV integrates a mobile phone application, allowing the driver to visualize all the information regarding vehicles in the vicinity, as well as event notifications and High-Definition Maps of the road, whenever this data is disseminated by the ITS Centre through the MEC broker. Figure 10 displays the app interface in the context of the HD-Maps User Story.

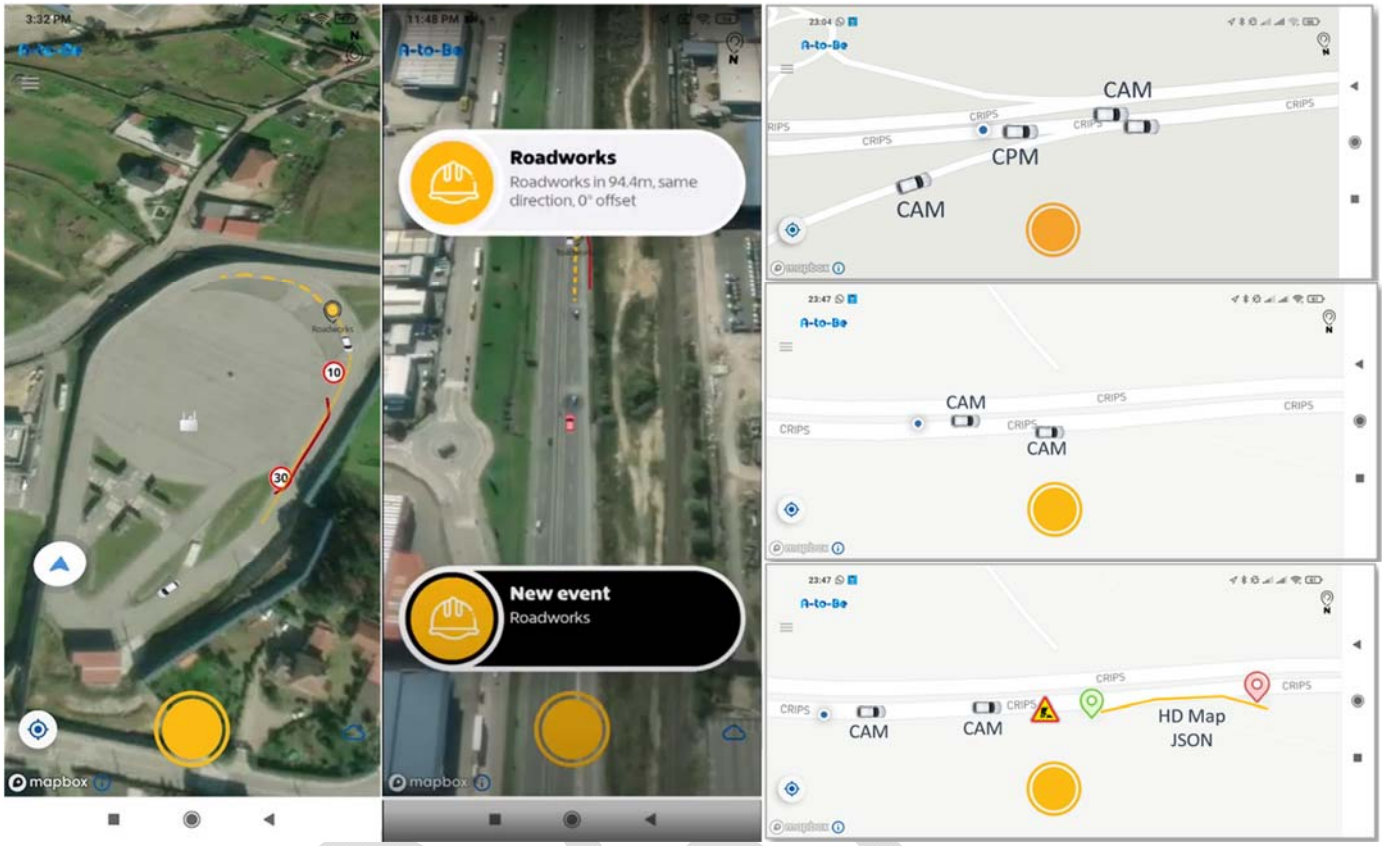

Figure 10: Mobile phone application of PT CV in the HD-Maps scenario.

3.2. Automated driving function development

Figure 11 depicts the high-level on-board software architecture of the autonomous vehicles participating in User Stories:

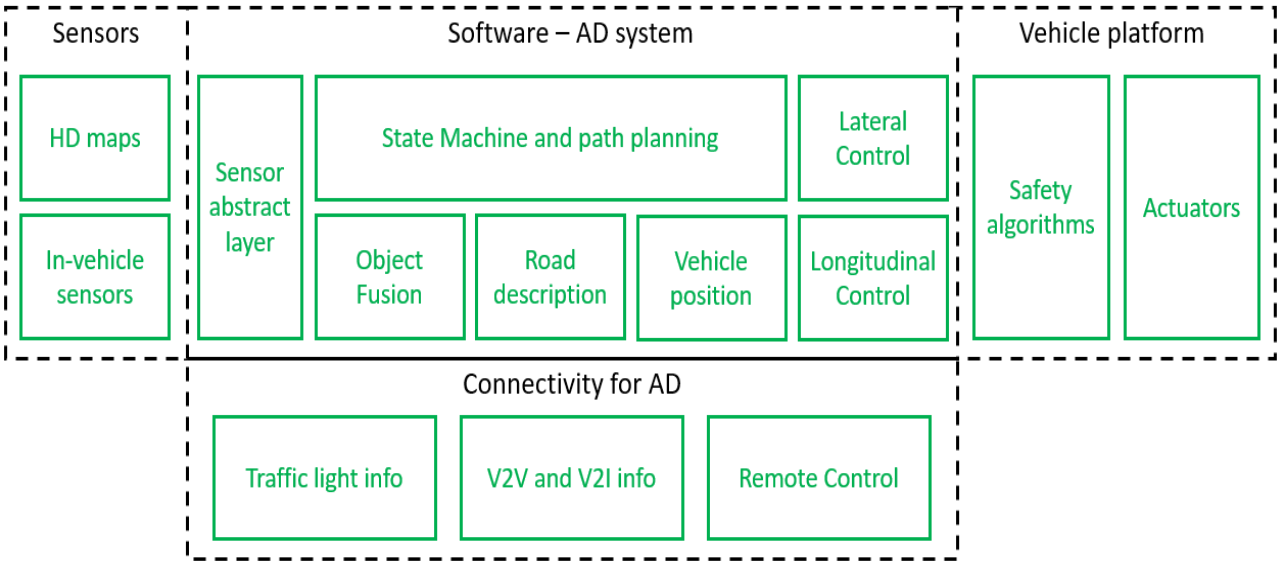

Figure 11: Automated driving high-level software architecture

As the figure above shows, all software components involved in AD managing functions are divided in 4 major blocks. These are described in detail in D2.4 (1) and a summary of them is given below. Please, note that the 5G OBU is not represented in that scheme because it is described in section 3.3.

Sensors: This block is related with all software created to retrieve information directly from the sensors.
AD system: In this block all AD functions are integrated. That is, all algorithm implementations responsible for making appropriate decisions based on the information received, take a roll for one or more of the autonomous operations of the vehicle.
Vehicle platform: Comprises the software to actuate on the vehicle depending on the information received by the AD functions and the safety algorithms ready to respond if needed.
Connectivity for AD: This block contains software in charge to receive information from external actors.

The software system presented above is employed to develop the UCC. Different parts of this system are involved in the different user stories, based on the needs to be fulfilled. In order to simplify the current deliverable and having detailed information in D2.4 (1), next sub-sections provide a brief description of the UCC and the software parts modified to carry out them.

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3.2.1. UCC#1: Advanced Driving at the ES-PT CBC

Advanced Driving UCC comprises three scenarios: "Lane merge", "Automated overtaking" and "Cooperative automated operation". In order to carry out these scenarios, the software development consisted on adapting the related automated driving functions, that is, customize the functions to take into account the zones where the User Stories will be developed and adding the new information provided by the 5G OBU and the roadside sensors and cameras.

3.2.2. UCC#3: Extended Sensors at the ES-PT Cross-Border

Extended Sensors UCC involves two similar scenarios with different vehicles: "HD maps" with autonomous vehicles, and "HD maps" with public transport. These scenarios required the development of new software components for automated driving functions and modifying the current version of other parts, as explained in the previous paragraph.

New Advanced Driver Assistance Systems Interface Specification (ADASIS 3) [1] was implemented to carry out scenarios on this UCC. ADASIS is a communication protocol recognized among the main OEMs in the market, created by the alliance between the mapmakers, OEMs and developers to be able to transmit all information available in a digital map abstracting from the format and location of the maps and that all this information can be interpreted by the ADAS system.

Due to this new addition, some AD software modules have been updated to work using this new interface In addition, AD functions were updated to get information about the new event on the road and to record it, sending this changes to the cloud unit, where this data will be processed to create the new map version that is then downloaded by other vehicles with the new changes.

3.2.3. UCC#4: Remote Driving at the ES-PT CBC

The Remote Driving UCC just contains the analogous scenario. This User Story required the development of several new software assets: on the one hand, a Remote Driving Cockpit has been built in CTAG facilities so that an operator can control vehicles from it; on the other hand, the Shuttle OBU has been adapted with new software for enabling remote driving capabilities.

The AD functions were adapted to use the commands sent by the cockpit and translate them to be understood by the vehicle's actuators.

In addition to that, a new communication protocol was developed by Nokia. Using the experience of all partners involved and after carrying out some internal test with proofs of concepts (PoC), the requirements of this protocol are:

[1] https://adasis.org/

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- It should be "Real-Time" meaning that the time interval between issuing a command and receiving the acknowledgement of the command should be less than 100 ms. The 100 ms budget was defined in the algorithm as a limit security requirement for round-trip latency. This requirement describes the acceptable limit for remote driving, the target being always a lower value. Typically, it is under 50ms. In fact, the application warns the user when the RTT times are in the range of 50-100 ms with a yellow colour in both the user interface in the VR Unity application and in the nodeJS online traces. One should note that for a vehicle moving at 10 km/h, 100ms means 0.27m of movement, not implying a risk in the remote driving procedure.
- It should be able to go through all the network topology end to end no matter which type of communications and devices are involved in every piece of the setup.
- It should not carry a big amount of data (e.g., it is not intended to transport video itself, but control commands related to video).
- Commands need to be tagged with unique IDs so that the system is able to detect non acknowledged or late acknowledge commands.
- It should be scalable.

Using the above requirements, a protocol with the following attributes is proposed:

- Periodic messages over the 5G network
- Command (CMD) message
    - From remote control to car
    - Contains: steering angle and target linear velocity + sequence number
- Acknowledgement (ACK) message
    - From car to remote control
    - Contains: actual steering angle, actual linear velocity, (others) + sequence number of CMD
- Periodic message with T = 100 ms
    - If no CMD message is received for 3T = 300 ms, the car stops because disconnection is assumed.
- Wire format to be defined. Initial proposal:
    - Message protocol: UDP
    - Payload: JavaScript Object Notation (JSON)

The mandatory messages for the protocol are:

- CMD (Control Order, only one client is accepted)
- ACK-TELEMETRY (ACKs to Control and Telemetry messages)

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- CMD-SUBS-TELEMETRY (Subscription to Telemetry messages, more than one is accepted)
- CMD-SUBS-VIDEO (Subscription to Video feed, more than one is accepted)

Other messages for future versions are:

- CMD-REG (Register in MEC, from old MEC)
- UNSUBS-TELEMETRY (Subscription to Telemetry messages)
- UNSUBS-VIDEO (Subscription to Video feed)
- GET-STATS (Get some statistics)

Currently, only CMD-REG is implemented. The other messages are not mandatory for the whole scenario to work.
A basic scenario can be shown below:

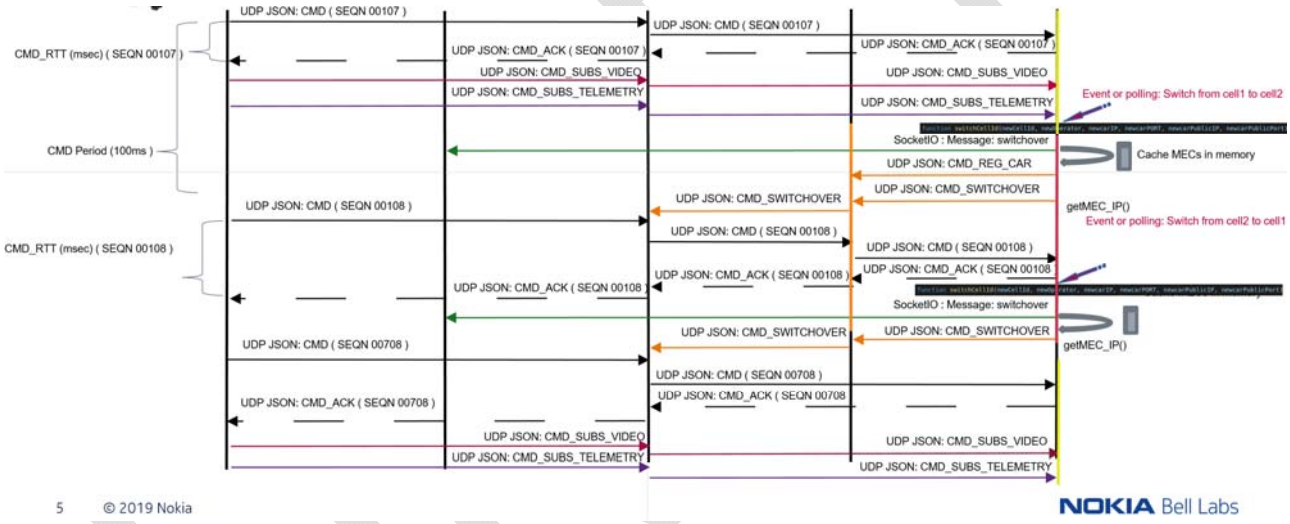

Figure 12: Remote Driving Protocol Scenario

This is the schema of the connectivity depicting the actors mentioned before for the case of one MEC.

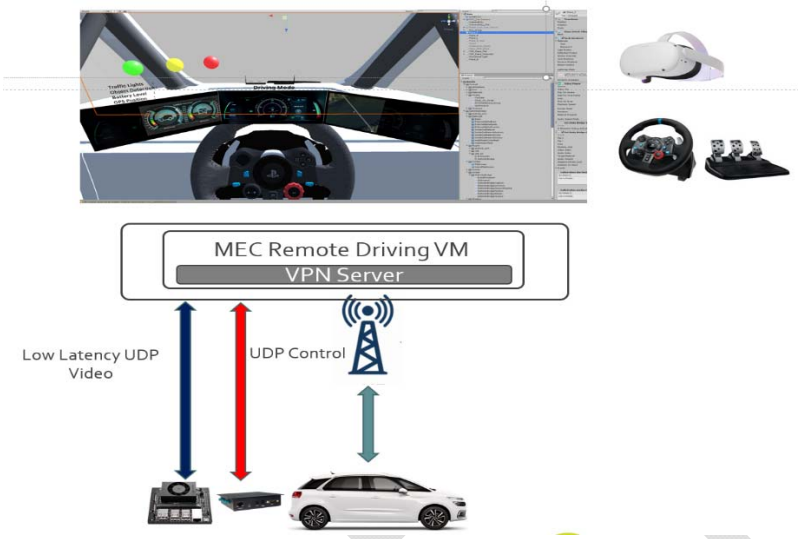

Figure 13: Remote Driving Actors

3.2.4. UCC#5: Vehicle Quality of Service Support at the ES-PT Cross-Border

Quality of Service UCC in the ES-PT CBC just involves scenarios where there are no autonomous vehicles involved and thus, there was no need to create or modify any AD driving functionality. Instead, new software components were implemented in order to capture, encode and stream the video from the 4K cameras to the ALSA Control Centre, and at the same time, the infotainment system was adapted for serving multimedia content available online.

3.3.OBU integration

The ES-PT CBC counts on three OBU models provided by different companies. These are: OBUs from CTAG (also called HMCU), OBUs from IT and OBUs from ISEL. The following subsections describe in detail the development and integration of these units.

3.3.1. CTAG 5G OBU

The OBU used in most of the vehicles participating in ES-PT User Stories is the HMCU, developed by CTAG and described in D2.4 (1). In order to adapt this OBUs for working as communication unit in 5G-MOBIX, some stages of development were necessary:

1. Integrate 5G chipset
2. Create and adapt low-level software elements for enabling the use of the 5G chipset.
3. Create and adapt high-level software elements in order to implement the required functionalities for the User Stories.

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The hardware architecture of the result OBU element after the integrations is shown in Figure 14:

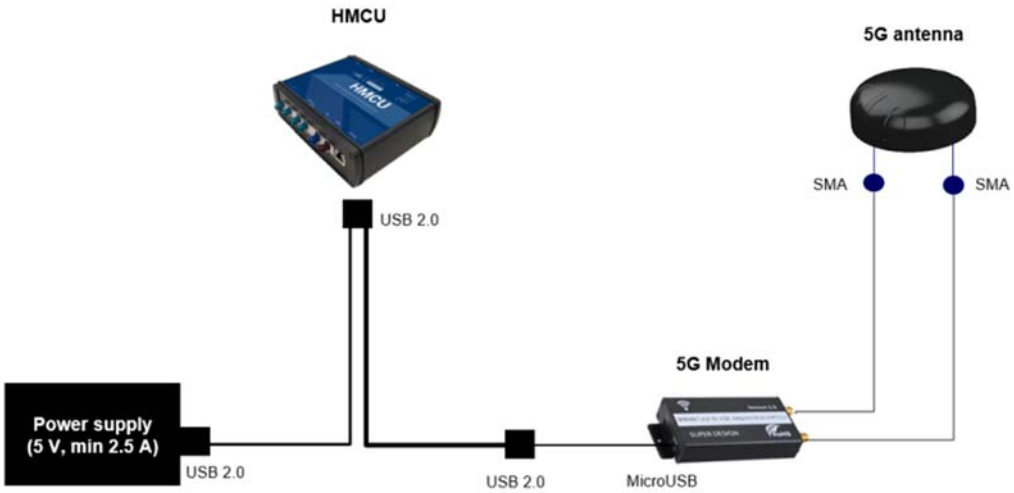

Figure 14: 5G OBU integration scheme

The 5G modem integrated by CTAG is the Quectel 5G RM500Q-GL model (Figure 15). It is a 5G Sub-6GHz M.2 Module for IoT applications, supporting LTE-A, 5G NSA and SA technologies. The use of external e-SIM is supported and it has a multi-constellation GNSS receiver, available for applications requiring fast and accurate fixes in any environment.

Figure 15: 5G Quectel chip 5G RM500Q-GL

The use of an M.2 to USB adapter is required to connect the modem to the external USB port of the OBU. The 5G module consumes more than 500mA (with peaks of about 1000mA), thus an external power source is needed.

The OBU firmware has also been adapted to include the required drivers to use the 5G modem. The Quectel Connect Manager tool is used to manage the connection configuration of the modem.

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The 5G antenna is a Poynting PUCK-2 model (Figure 16). It is a 2x2 MIMO omnidirectional antenna that cover the 698 to 3800 MHz band, suitable for automotive use.

Figure 16: 5G Antenna

Even though the 5G module and the 4G module are connected to different ports, they are incompatible since they use different software to manage the internet connection. For this reason, it is necessary to physically disconnect the 4G modem from the OBU's PCI port.

The modem-manager software has also been adapted to manage the 5G modem service, ignoring the 4G modem.

In Figure 17 some steps of the adaptation of the OBU to get 5G connectivity are shown.

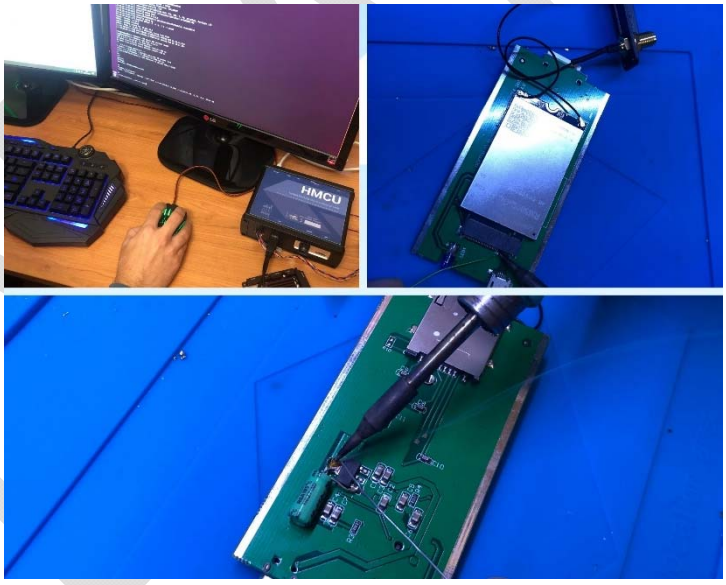

Figure 17: 5G modem integration process

3.3.2. PT OBU

The PT connected vehicle is not equipped with any automated driving functionalities, being solely fitted with a 5G OBU, a dashboard smartphone and a GNSS receiver (Figure 18). The vehicle's OBU integrates a 5G Quectel module (RM500Q-GL) in an Advantech network appliance (FWA-1112VC) for V2N/N2V communications. The smartphone is used to display information to the vehicle's driver and other

passengers. The GNSS Trimble is integrated on the roof of the car and it allows accurate geo-localization of the vehicle. A 5G dome antenna with magnetic mount from Panorama Antennas is used on top of the vehicle for improved 5G signal.

Figure 18: PT Connected Vehicle Architecture

The 5G OBU is also connected to a Time Server machine (Figure 18) with the sole purpose of providing a precise source for clock synchronization, using the Pulse Per Second signal available in an independent GNSS receiver. This accurate time synchronization is very important for the logging and evaluation measurements of KPI metrics, such as communications latency in a 5G setup. The Precision Time Protocol (PTP) is used to synchronize the 5G OBU to the Time Server.

The OBU subscribes to the topics of interest in the MEC MQTT broker, namely the ones regarding CAM, DENM and CPM messages, as well as the HD Maps JSON updates. The OBU also publishes CAM messages with vehicle parameters in the appropriate broker topic. All these messages are forwarded to the V2X App, through a Wi-Fi connection with the OBU also using MQTT protocol. Subsequently the messages are displayed in the smartphone's HMI for driver awareness (Figure 19: (a) Lane merge example. (b) Overtaking scenario and (c) HD Maps scenario).

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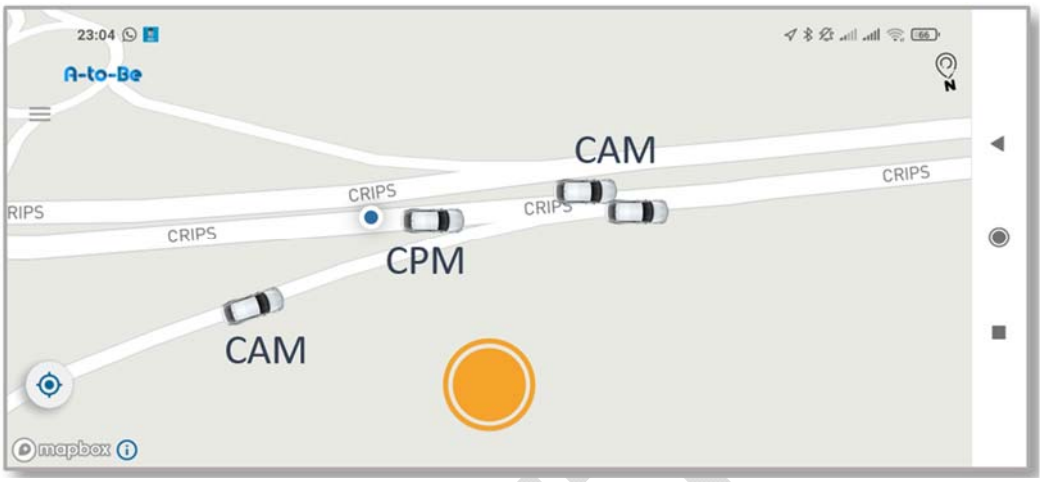
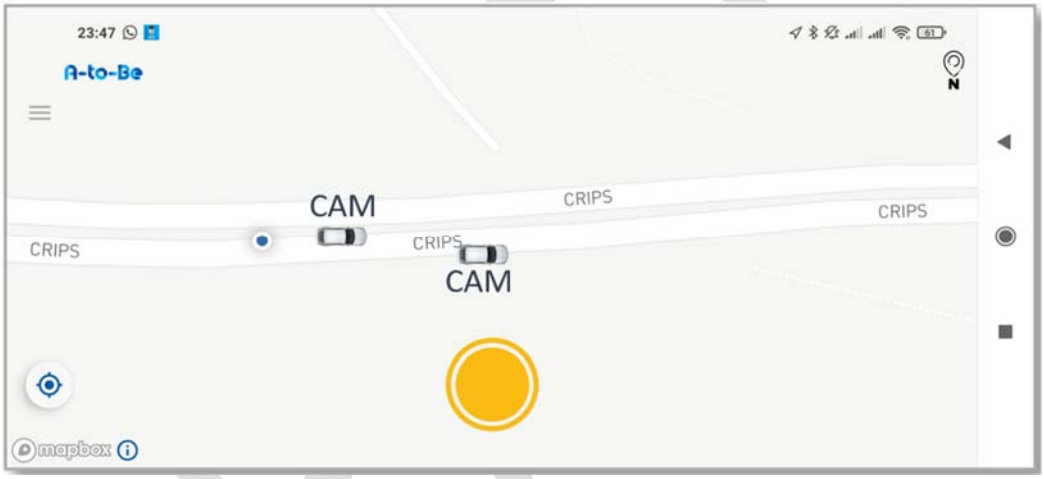
(a)



(b)



(c)

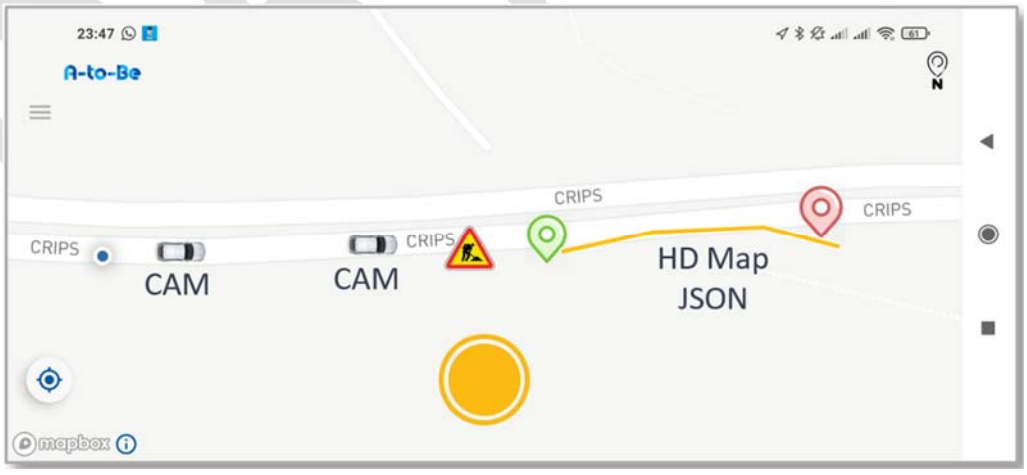


Figure 19: Smartphone Application in the PT Connected Vehicle.

3.3.3. ISEL OBUs

ISEL developed the IQ-NPE platform dedicated to generate multiple traffic sources over 5G networks and simultaneously measure different KPIs at different POC in the network. An essential part of this platform are OBU capabilities and their modems. The developed architecture for the OBU is presented by Figure 20. here a 4G/3G extra modem was added (using a public network) to remotely control the OBU functions. Local wired interfaces are also available. For the 5G measurements, the OBU HW allows an integration of (up to) 3 modems, contributing to stress the network with high demanding applications and multiple data traffic streams. Using this strategy, it is possible (and combining more OBU with 3 modems each) to stress the network or generate background traffic, while autonomous and connected vehicles perform the UC/US using CCAM based applications. Being this function relevant to assess the network performance while being used by other 5G users and their demanding applications.

Moreover, these OBUs and the IQ-NPE platform enable the agnostic scenarios measurements, since they can generate multiple sources of traffic, such as CAM, CPM, DENM, MQTT messages, PING, HTTP, SFTP, TCP/IP, UDP/IP and other traffic sources based on scripts.

Figure 21 shows two OBU installed in a vehicle, where it is possible to observe coaxial cables connecting outside antennas (Figure 22) to internal modems. In the middle of the figure we can observe the GNSS terminal and antennas used by the NTP system that increase the time synchronisation with the MEC. The OBU machine is the NEXCOM VTC 7251 Fanless Vehicle Compute model. The selected modems are provided by Thales Cinterion, with the model MV31-W.

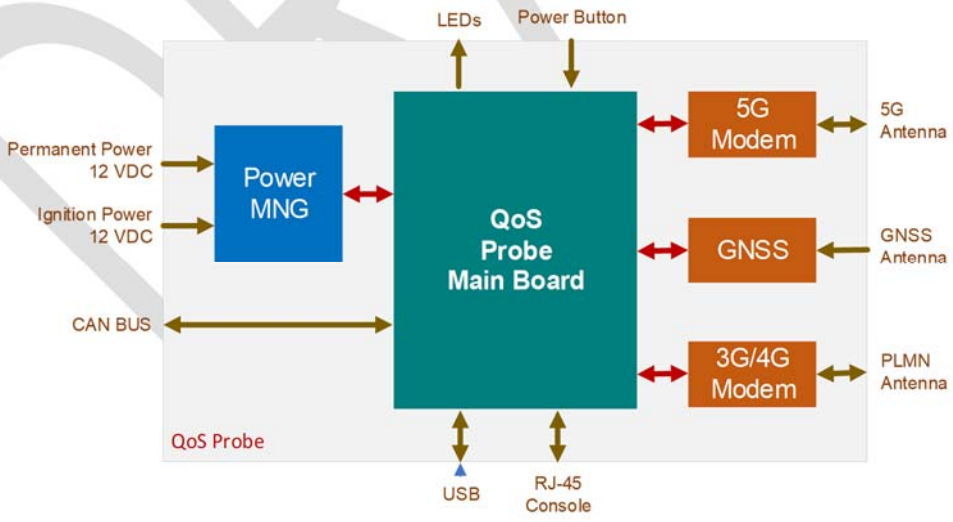


Figure 20: IQ-NPE OBU internal architecture

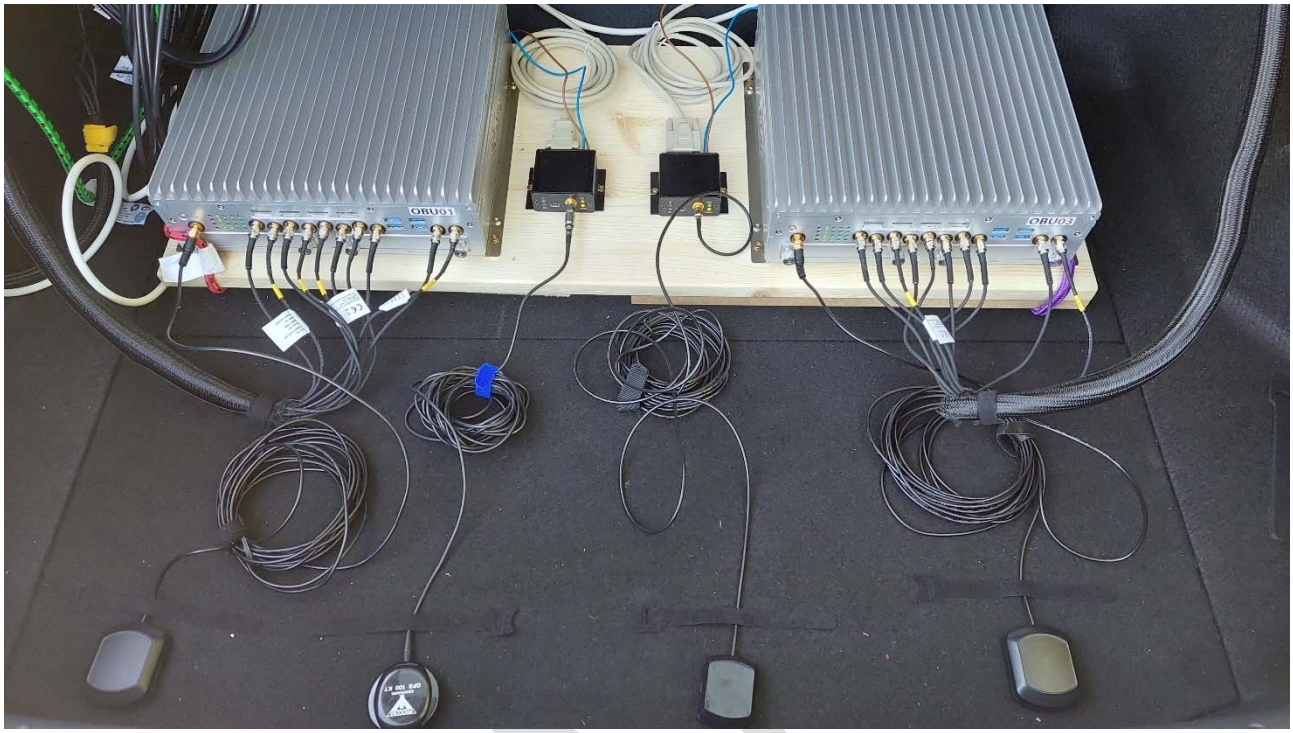


Figure 21: IQ-NPE 2 OBU installed in a vehicle

Figure 22: IQ-NPE 5G modems antennas installation

Figure 23 presents OBU internal functional blocks, where external interfaces/modules are presented, such as 3G/4G external remote access (management and console functions), 5G modems interfaces, GNSS module interface, CAN interface, the QoS Tests Manager, which is essential to control and launch tests, and finally the Probe Core, which takes care of results management and deals with external interfaces such the IQ-NPE platform.

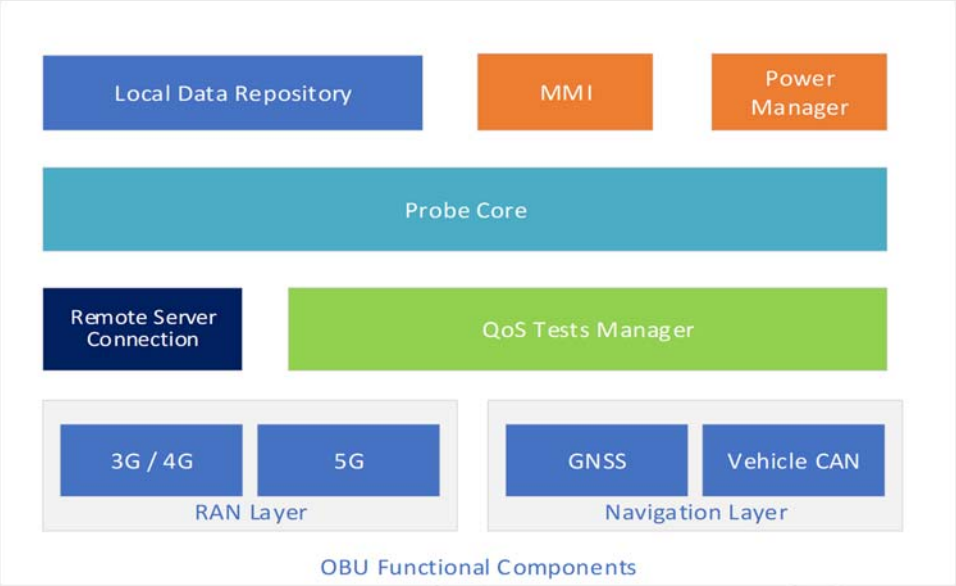


Figure 23: IQ-NPE internal functional blocks

3.4. TS contributions to ES-PT vehicles / OBU

After long discussions within the project consortium, the ES-PT CBC has agreed to collaborate with 4 TS (NL, FI, FR, DE) to complement their User Stories and achieve more comprehensive results. In particular, some of these collaborations complement the work done by the ES-PT corridor partners on the development of in-vehicle applications and OBUs:

- Distributed (in-vehicle-based decision making) or centralised (infrastructure-based decision making) decision making will be benchmarked, analysing how 5G affects each approach, in the context of an autonomous overtaking manoeuvre together with the Dutch partners.
- A service discovery system provided by the Finnish partners will be implemented to find, in a scalable way, the cloud resources available in each operator's network in order to execute an HD map update across a border.
- Interoperability between connected and autonomous vehicles from different providers will be demonstrated with the help of French partners.
- OBUs with different designs and from different vendors will be used under the same cross-border conditions to compare their performance and functionality in terms of connectivity and network changes. This scenario will involve Finnish and French partners.
- All these collaborations are described in detail in deliverable D3.6.

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3.5. Early testing results

3.5.1. CTAG early tests

After a long process of sensors and equipment integration and software development, as described in previous sections, CTAG has performed an important amount of partial tests before getting their vehicles fully working for testing User Stories. The following sections describe some of the preparations and tests performed during the integration and development process.

3.5.1.1. LiDAR sensors calibration and test

During the sensor's integration process, some firsts tests were performed in order to verify the correct placement of the LiDAR sensors in the vehicles and to calibrate them, i.e., introduce exact yaw, pitch and roll angles so that possible deviations from the intended target values could be compensated by software. All these preliminary tests were implemented indoors within the facilities or at CTAG's testing track.

Calibration process for Velodyne VLP16s.

Part of this calibration was done in CTAG's testing track, by placing the vehicle in front of a wall. By analyzing the difference in distance among the 16 sensor layers, actual pitch and roll could be easily estimated. In order to determine sensor's yaw, the position of a thin target (typically a post) aligned with the middle axis of the vehicle was inspected. This was done within CTAG's facilities as it was easier to obtain references to ensure the target's desired position.

Desired calibration for shuttle's VLP16s was (pitch = -10º, yaw = 0º, roll = 0º). For the vehicles no pitch was intended, so desired calibration was (pitch = 0º, yaw = 0º, roll = 0º). However, in practice, small deviations were always present. These deviations were compensated by the LiDAR processing software (unless they were big enough to invalidate the whole integration). Figure 24 shows a point cloud used for calibrating the Velodyne sensor.

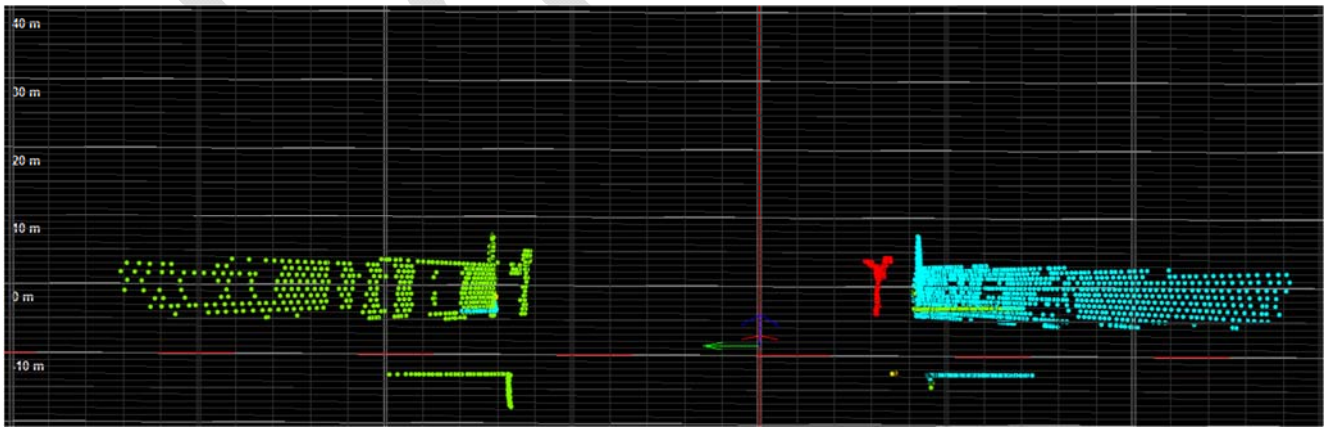

Figure 24: VLP16 calibration typical scenario

Calibration process for Valeo Scalas.

The whole calibration was done within CTAG's facilities, just needing a flat and empty ground in the first 15 meters in front or behind the vehicle (depending on whether front or rear LiDAR was being calibrated). By inspecting the shape and distance where the first layer was hitting the ground, we could ensure pitch and roll were 0º as intended. If this was not the case, sensor holder was regulated until the required effect was seen in the point cloud. Figure 25 shows a point cloud used for calibrating the Valeo Scala sensor.

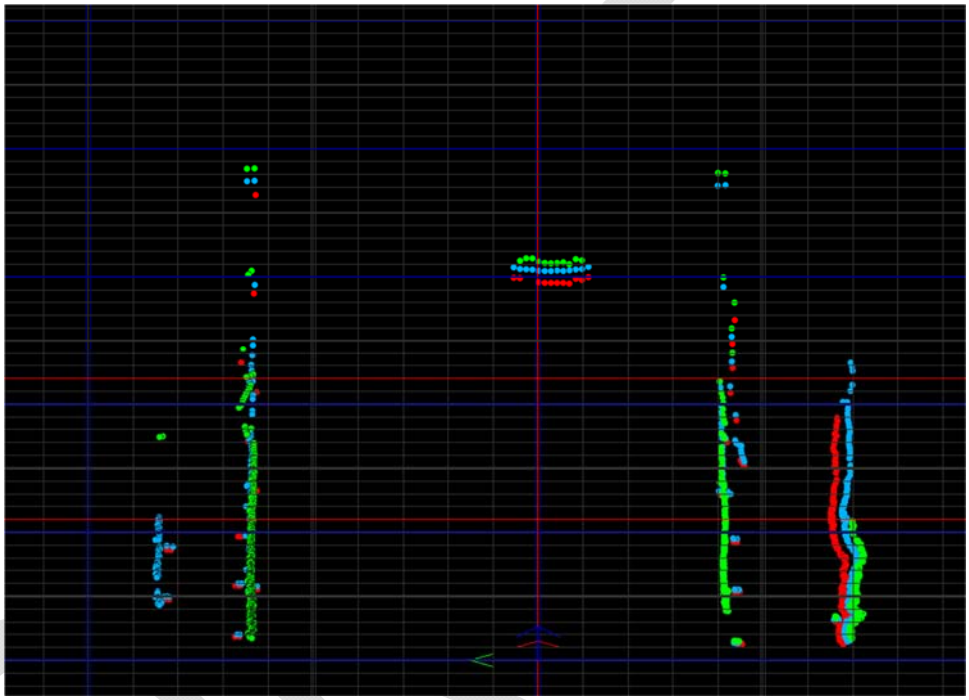

Figure 25: VLP16 calibration typical scenario

Calibration process for Sicks.

The whole calibration was done in CTAG's testing track, within an urban-like scenario where a crossroad was reproduced with walls in a four-corner arrangement. Sick TIM-561s in the shuttle were calibrated by inspecting their provided distances to the walls and comparing them to reality. Also, coherency between the three point clouds was tested in order to see not only whether their orientation was correct, but also if they were consistent among each other.

Basic object detection tests.

For all sensors working together, either if they were installed in a car or in the shuttle, early detection tests were carried on in the testing track.

First of all, static tests where another car or several pedestrians were placed at different distances, orientations and azimuth angles with regard to the tested vehicle were made. Not only the expected point cloud was checked, but also the results of the processing algorithm, which needed to provide the expected position (X and Y) and velocity (0 km/h) of the detected object.

After that, dynamic tests were made, where the equipped vehicle followed a moving target (other vehicle) around the track. During this test, some logs were recorded for later analysis in the office. Position and velocity (velocity should be similar to that of the ego, slightly higher when separating, slightly lower when approaching) were checked.

A short drive within the facilities was finally made in order to evaluate the likelihood of the system to provide false detections which could be due to a bad configuration or a faulty installation.

All these verifications showed the expected results before any of the use cases related to the project were tested.

3.5.1.1.1. Camera detection preparation and testing

Once that camera sensors for object detection were integrated in the shuttle, some individual tests took place both in test track and in the real scenario for checking system functionality and stability.

First tests were performed in test track, providing very promising results in terms of object detection (accuracy of the detection and tracking of the object) and anticipation for a safe break.

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Figure 26: Good detection of the object from a far distance while vehicle is approaching to it.

However, the results at the selected location for the final tests were not as good as the ones obtained on test track. Shadows that occurred due to the bridge' structure affected badly the deep learning module in charge of performing the object detection and classification task. Apart from that, the usage of dummies instead of real pedestrians also influenced in a bad way the final performance, since the model was trained with real pedestrians, but not with "dummies".

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Figure 27: Dificult detection of dummy inside the bridge due to shadows. Good detection of pedestrians out of the bridge without shadows. Good detection of pedestrians with shadows.

Different supported object detection models were analysed and tested to improve the system performance, some of them giving better accuracy results on target detection. But in those cases the real-time requirement was not met, so those options were finally discarded.

With the intention of improving the performance of the perception layer, it was decided to use LiDAR sensors for complementing to the vision algorithms achieving enough redundancy at perception level for accomplish the User Story.

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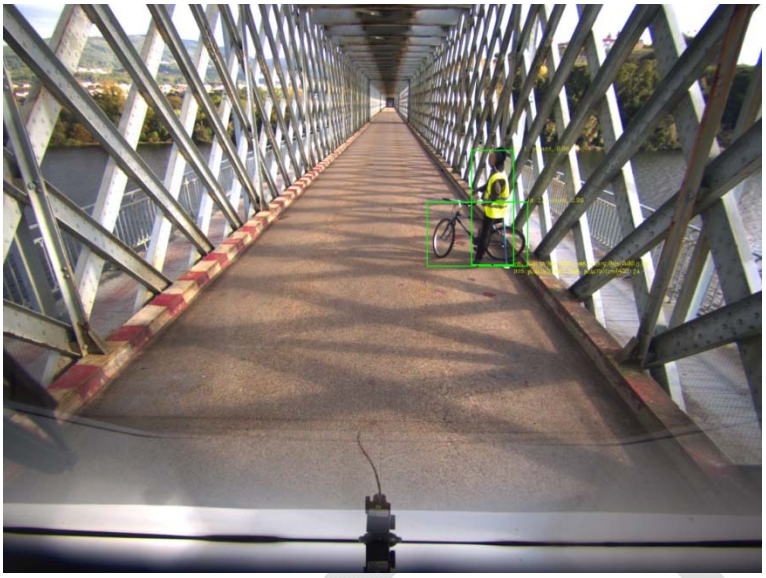

Figure 28: Accurate detection results using camera and LiDAR sensors jointly.

3.5.1.2. *Autonomous functions testing*

During the development process of the autonomous functionalities, various testing stages take place before having the vehicles driving autonomously:

- Model in the loop test (MIL): the software functions are simulated in MATLAB/Simulink using both synthetic inputs -to test against the ideal scenario- and real-world data inputs recorded with the vehicles.
- Hardware in the loop (HIL) test: in the next step the software functions are simulated in the HIL bench. This bench is equipped with some of the different hardware subsystems that are installed on the vehicles. These tests are mainly aimed to test the integration between the Autonomous Driving platform and the rest of subsystems. On both MIL and HIL tests, we focus on testing the functionality assuming an ideal connectivity with no latency.
- Test track tests: the next step is to test the different scenarios on CTAG's tests tracks. In order to do this, the most important parts of the project scenarios will be reproduced on CTAG's test track. Also the proximity of the test track to the project scenarios makes possible to have access to the 5G network, so it can be used during the test sessions.

3.5.1.3. *Internal HD map preparation*

CTAG is currently working on one of the most important features to improve the capabilities of autonomous vehicles such as the provision of HD maps. These maps are highly defined which allows the vehicle to have a wider horizon to make decisions based on the elements of the environment. These maps provide an extremely relevant and valuable input to the autonomous function.

The generation of these high-definition maps involves two phases:

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- The first phase. --> The recording of the real scenario with a car equipped with all types of sensors (camera, IMU, LiDAR…) and equipment that allow the acquisition of all the lines and characteristics of the road and static elements that conform the map (signs, traffic lights, railings, guardrails, guardrails, road limits…).
- The second phase --> Involves the processing of the collected data with the developed algorithms to analyse the recordings and to compile the map according to the initial requirements for the final execution of the function in the autonomous vehicle.

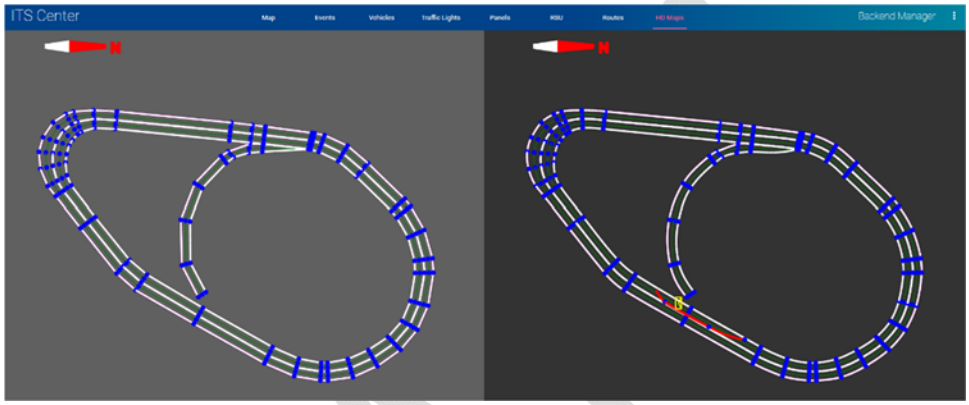

Figure 29: Database content

The collected data are stored in CTAG's own database with a predefined structure for this project. Once the database has been generated, it is verified to ensure that it fulfils all the requirements defined using a validation script. Additionally, it is verified that the generated map has the appropriate geometry by comparing it with a real map (e.g. Google maps). This is done with a CTAG proprietary application that has the function of drawing the created map over this real map and checking that it has the right shape.

Figure 30: Created map over real map

Once this validation process of the requirements requested for the map is correct, the database is installed in the Maps & Perception unit.

Following this process, a HD map of the test track was created and installed in the unit, after which it was used to extract the necessary line and events information to drive in autonomous mode on that ground. Logs were recorded and checked in the office to make sure the HD maps provider system was working and all information was being retrieved correctly.

3.5.1.4. Vehicle architecture

In order to ensure that all the vehicle systems are functional prior to the trials, preliminary tests have been carried out in the real scenarios with CTAG vehicles in manual mode, but with active equipment for testing sensors, network coverage, GPS correction coverage, HD Map data and function output offline. As an outcome of this process, many systems have logged their performance and functionality, enabling the offline validation and error-correction for improving the overall system. Likewise, during all these preliminary tests (both in real scenarios and in the test tracks) many adjustments and hardware issues resulting from the integration have been detected and corrected.

During all the entire testing stage, a detailed monitoring of the overall vehicle architecture (Figure 31) has taken place so that any possible issue or incompatibility could be found and corrected.

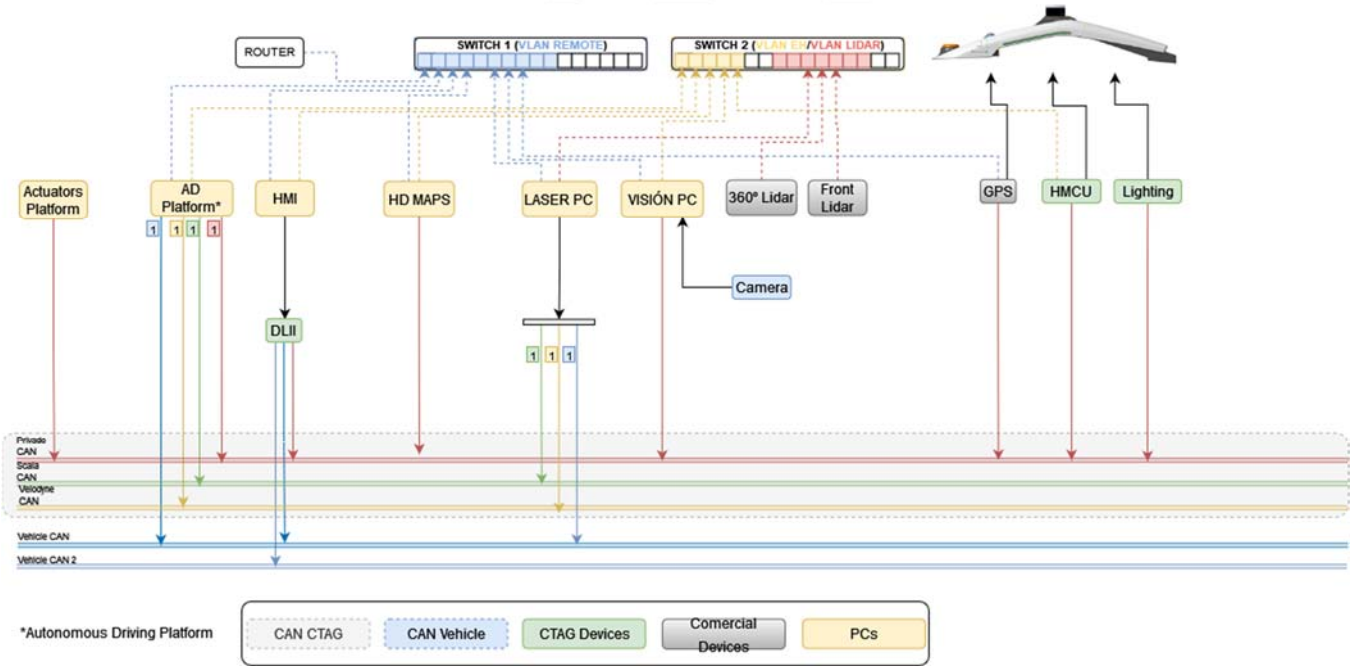

Figure 31: Vehicle system architecture

3.5.1.5. First tests with the 5G OBU

Just after the integration of the 5G modem in the CTAG OBU, several functionality tests have been carried out in order to assure that the modem was providing appropriate connectivity.

The first tests in this development stage were focused on finding out the behaviour of the available 5G network with the OBU modem. For this purpose, it was necessary to check previously the coverage of the 5G antennas. With a mobile phone and the nPerf[2] application, it was possible to take a first approximation of the range and the speed of the 5G connection, shown in Figure 32.

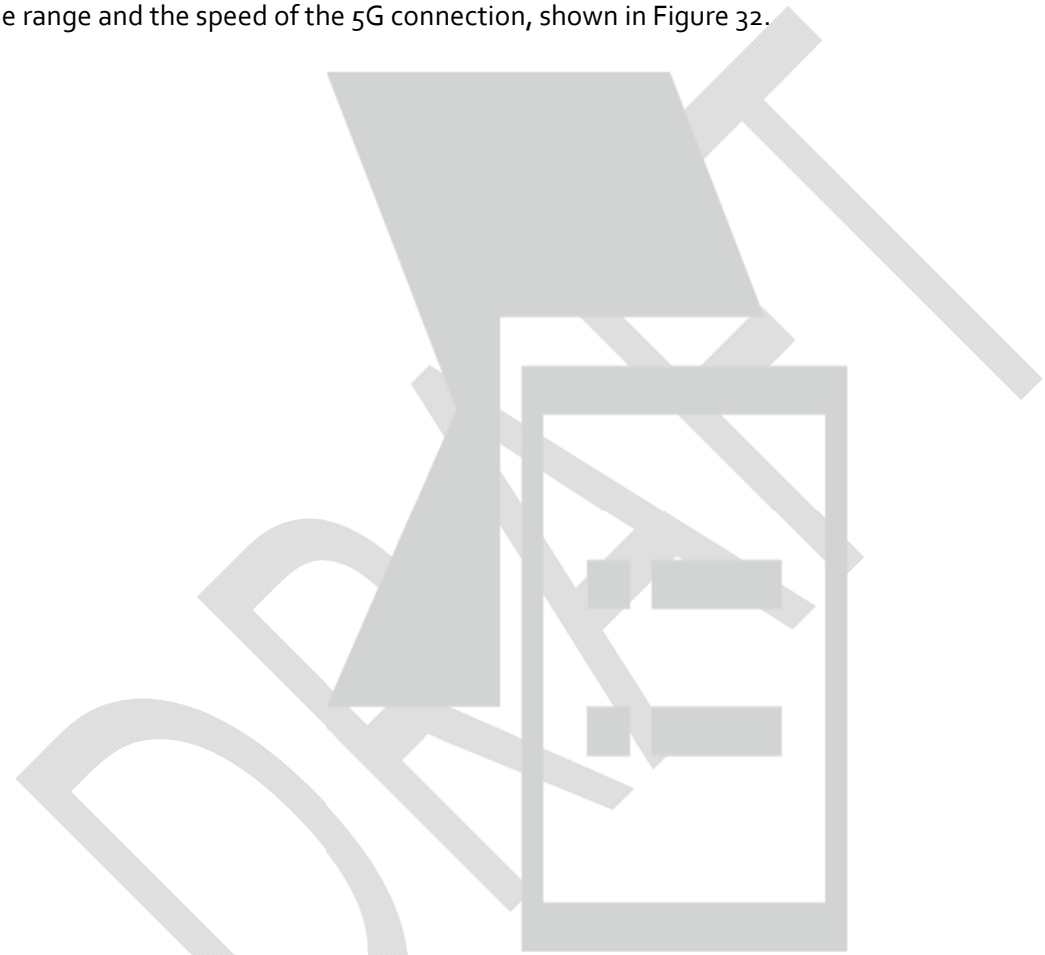

Figure 32: Capture of Nperf application

After this basic characterisation of the network with a mobile phone, and knowing where 5G coverage was present, the second testing stage came in: to connect the OBU to the 5G network for the first time (Figure 33), and to make some first throughput tests (Figure 34).

[2] https://www.nperf.com/es/

Figure 33: Capture of first attach to a 5G NSA network with CTAG 5G OBU

Figure 34: Capture of the first throughput test on CTAG 5G OBU

It must be noticed that the network which the OBU was connected to on those experiments was a Telefonica commercial network (plmn 21407) different from the Telefonica pilot network (plmn 21438), which hadbetter performance.

The conclusion of those tests was that the 5G modem had been successfully integrated into the CTAG OBU. It was ready for going through the following phase: the application development and testing.

3.5.1.6. 5G OBU applications preparation and testing

Connection with the MEC

- Connection tests with the MEC from the OBU

In these tests, the connection of the MQTT client of the OBU against the MEC has been verified, without using security mechanisms (using a given user and password as connection data). It has been verified that the client connects correctly with the MEC.

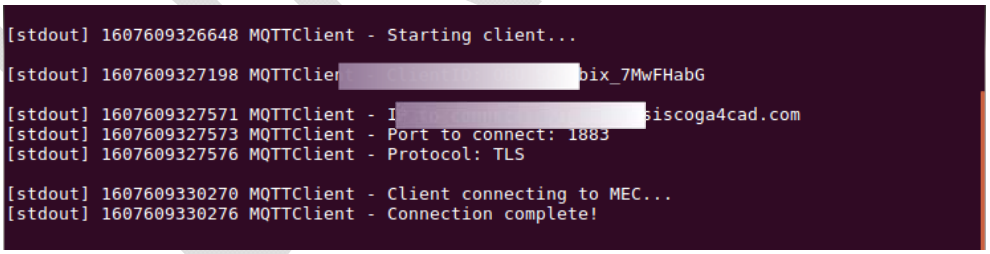

Figure 35: Result of the connection of the MQTT client of the OBU against the MEC

- Disconnection and reconnection tests with the MEC from the OBU

In these tests it has been verified that when the MQTT client of the OBU loses connection with the MQTT, it tries to reconnect automatically until the connection is established again.

The chain of several successive reconnections has been tested: the client disconnection chain is repeated several times (the MQTT client connects to the MEC, soon the connection is lost and the reconnection state is entered until the connection is established again and the client processes are established on a regular basis) during the same SW execution. In this way, it is verified that the MQTT client is able to reestablish, as many times as necessary, the connection in case of loss of the same for various reasons (loss of output to the Internet, disconnection of the MQTT client by the server, etc.)

In addition, through these tests, the connection times and the MQTT client reconnection attempt time have been adjusted so that possible disconnections with the MEC imply the least possible loss of information.

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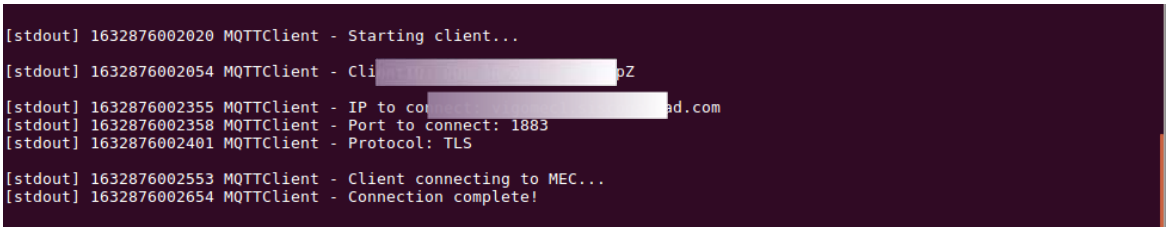

Figure 36: Result of the execution A of the SW of the OBU (the connection against the MEC is established for the first time)

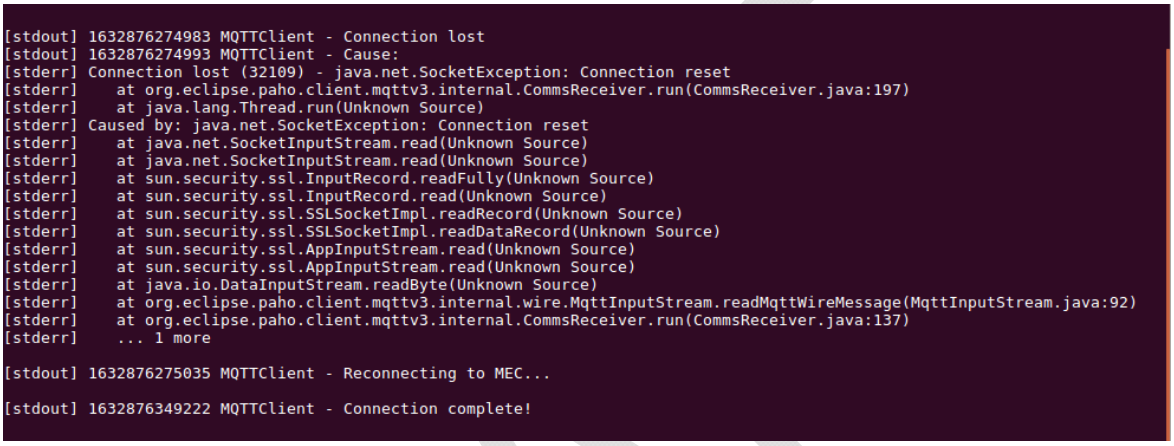

Figure 37: Result of execution A of the SW of the OBU (the connection against the MEC is lost, the reconnection attempt is initiated and the client is connected a second time)

- Connection tests with the MEC with security (JWT)

In these tests, the different points that are included in the complete connection chain have been checked with security.

Specifically, the security connection tests performed are as follows:

- It has been verified that the POST request for tokens is correctly formed from the OBU (including the corresponding parameters and their signature, as well as other processes defined in the project for this request).
- It has been verified that the POST request is sent correctly to the MEC, and a valid code is obtained in response.
- It has been verified that, in the area of Spain, the response obtained by the MEC when making the POST request is an array of tokens (length 1), which contains the connection information with the Spanish MEC.
- It has been verified that, in the border area, the response obtained by the MEC when making the POST request is an array of tokens (length 2), which contains the connection information with the Spanish MEC and the connection information with the Portuguese MEC.

- It has been verified that, in the area of Portugal, the response obtained by the MEC when making the POST request is an array of tokens (length 1), which contains the connection information with the Portuguese MEC.
- It has been verified that the SW of the OBU is able to obtain the necessary information from the tokens received by the MEC, and the connection of the MQTT client is made correctly from that data.

Figure 38: Result of the formation of the POST request, and response obtained by the MEC

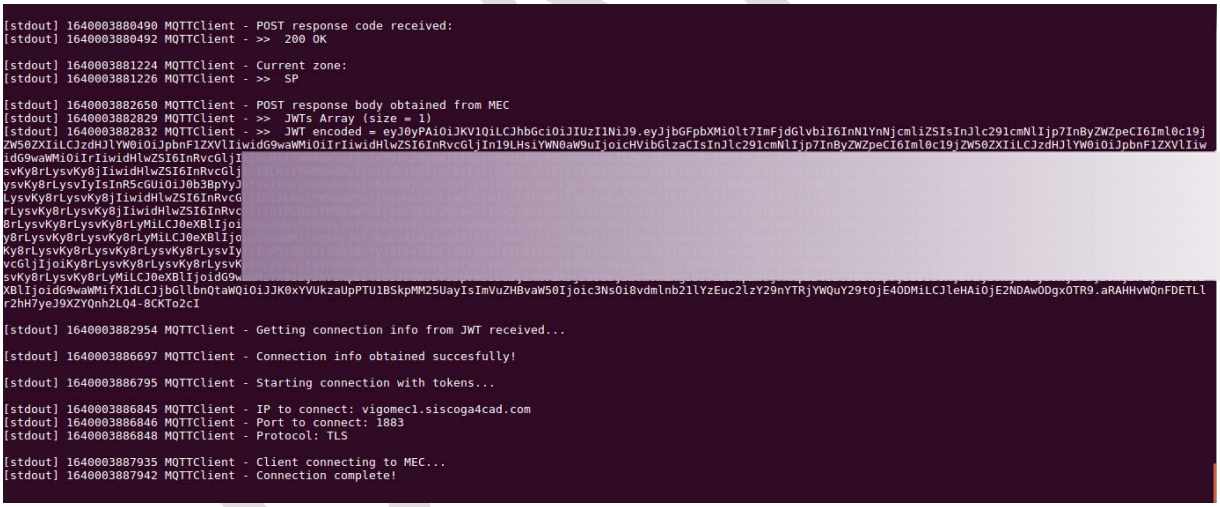

Figure 39: Result of obtaining the information from the received token, and connection of the MQTT client with that data

In addition, it has also been verified that the MEC sends a notification to the OBU as soon as the registration zone is changed (Spain, Portugal or border), and that it makes a new request for tokens to obtain the new connection information for the geographical area in which it is located.

**NOTE: All these tests were performed first locally and then against the final MEC.*

Management of geographical areas

- Subscription testing and calculation of geographic cells

In these tests it was found that the MQTT client of the OBU is able to calculate the geographical position in which the vehicle is located, as well as the adjacent geographical cells, from its GPS position. This calculation has been verified to be performed correctly for the different zoom levels of the cells. From the calculated geographic cells, subscription topics are formed for CAM, DENM, and CPM messages.

In addition, it was verified that the MQTT client subscribes correctly to the topics of the MEC (which include the corresponding geographical cell). Specifically, nine subscriptions are made (one to receive the information in the geographical cell in which the vehicle is located, and another 8 to receive the information in the adjacent geographic cells) for each type of message (CAM, DENM and CPM).

```
[stdout] 1607609335731 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/3/# (central tile)
[stdout] 1607609335778 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/1/# (adjacent tile)
[stdout] 1607609335801 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/0/1/# (adjacent tile)
[stdout] 1607609335820 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/3/2/# (adjacent tile)
[stdout] 1607609335840 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/2/# (adjacent tile)
[stdout] 1607609335860 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/0/# (adjacent tile)
[stdout] 1607609335886 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/0/0/# (adjacent tile)
[stdout] 1607609335905 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/3/0/# (adjacent tile)
[stdout] 1607609335925 MQTTClient - Subscribed to its_center/outqueue/cam/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/1/0/# (adjacent tile)

[stdout] 1607609335945 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/3/# (central tile)
[stdout] 1607609335970 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/1/# (adjacent tile)
[stdout] 1607609335996 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/0/1/# (adjacent tile)
[stdout] 1607609336015 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/3/2/# (adjacent tile)
[stdout] 1607609336035 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/2/# (adjacent tile)
[stdout] 1607609336055 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/0/# (adjacent tile)
[stdout] 1607609336073 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/0/0/# (adjacent tile)
[stdout] 1607609336101 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/3/0/# (adjacent tile)
[stdout] 1607609336122 MQTTClient - Subscribed to its_center/outqueue/denm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/1/0/# (adjacent tile)

[stdout] 1607609336145 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/3/# (central tile)
[stdout] 1607609336165 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/1/# (adjacent tile)
[stdout] 1607609336185 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/0/1/# (adjacent tile)
[stdout] 1607609336205 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/3/2/# (adjacent tile)
[stdout] 1607609336220 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/2/# (adjacent tile)
[stdout] 1607609336240 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/2/0/# (adjacent tile)
[stdout] 1607609336260 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/0/0/# (adjacent tile)
[stdout] 1607609336282 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/0/3/0/# (adjacent tile)
[stdout] 1607609336305 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/1/1/2/1/0/# (adjacent tile)
```

Figure 40: Result of MQTT customer subscriptions to receive CAM, DENM and CPM messages published in the vehicle area

**NOTE: All these tests were performed first locally and then against the final MEC.*

Management of data received and sent through the MEC

- Tests for forwarding information between the EQF input and output queues

In these tests it has been verified that the CAM, DENM and CPM messages published from the OBU in the entry queue of the MEC ("inqueue"), are published again by the MEC in the exit queues of the same ("outqueue") corresponding to the geographical cell where the vehicle is located (from where the information is initially published) and in the adjacent geographical cells.

In this way, it is verified that the vehicle publishes the messages in the entry queue of the MEC corresponding to its geographical area and that, being previously subscribed, it receives that same information in the corresponding MEC exit queues.

Figure 41: Result of the test of emission and reception of the same CAM message through the input and output queues of the MEC (central and adjacent area)

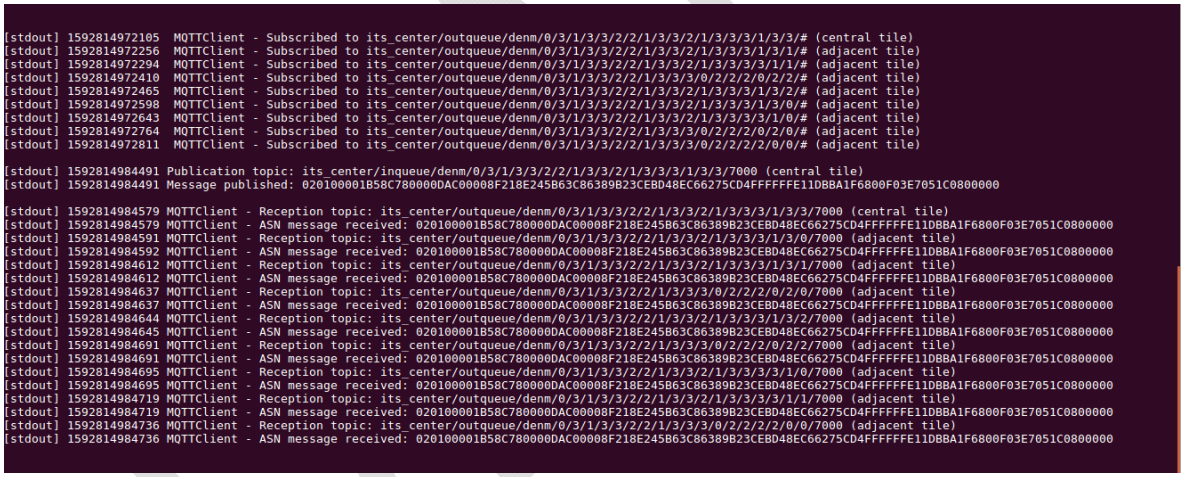

Figure 42: Result of the test of emission and reception of the same DENM message through the input and output queues of the MEC (central and adjacent area)

```
[stdout] 1593447680464 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/3/# (central tile)
[stdout] 1593447680508 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/1/# (adjacent tile)
[stdout] 1593447680549 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/3/1/1/# (adjacent tile)
[stdout] 1593447680589 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/3/0/2/2/2/0/2/2/# (adjacent tile)
[stdout] 1593447680632 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/2/# (adjacent tile)
[stdout] 1593447680676 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/0/# (adjacent tile)
[stdout] 1593447680729 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/3/1/0/# (adjacent tile)
[stdout] 1593447680776 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/3/0/2/2/2/0/2/0/# (adjacent tile)
[stdout] 1593447680824 MQTTClient - Subscribed to its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/3/0/2/2/2/2/0/0/# (adjacent tile)

[stdout] 1593447701594 MQTTClient - Publication topic: its_center/inqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/3/14 (central tile)
[stdout] 1593447701595 MQTTClient - Message published: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02

[stdout] 1593447701662 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/3/14 (central tile)
[stdout] 1593447701662 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701701 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/0/14 (adjacent tile)
[stdout] 1593447701701 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701742 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/1/14 (adjacent tile)
[stdout] 1593447701742 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701779 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/3/0/2/2/2/0/2/0/14 (adjacent tile)
[stdout] 1593447701781 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701796 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/1/3/2/14 (adjacent tile)
[stdout] 1593447701806 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701831 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/3/0/2/2/2/0/2/2/14 (adjacent tile)
[stdout] 1593447701831 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701844 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/3/1/0/14 (adjacent tile)
[stdout] 1593447701845 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701868 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/2/1/3/3/3/3/1/1/14 (adjacent tile)
[stdout] 1593447701868 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
[stdout] 1593447701882 MQTTClient - Reception topic: its_center/outqueue/cpm/0/3/1/3/3/2/2/1/3/3/3/0/2/2/2/2/0/0/14 (adjacent tile)
[stdout] 1593447701882 MQTTClient - ASN message received: 010E00000000DC48101F3AF495D1989D1DB3FFFFFF8476EE87C00000002C988359B3204DACD0AB72C035FC02
```

Figure 43: Result of the test of emission and reception of the same CPM message through the input and output queues of the MEC (central and adjacent area)

- Latency measurement tests in the send-receive flow of messages

In these tests, an average value of the time intervals between a vehicle publishing information, until another different vehicle receives it, was calculated.

Specifically, the time from when the MQTT client of the OBU "A" (vehicle "A") sends a CAM, DENM and CPM message to the MEC through the input queue, until it is received by the MQTT client of the OBU "B" (vehicle "B") through the output queue of the MEC to which it is subscribed has been analyzed.

This process has been run several times to get an average value of these latencies.

Vehicle "A"	Vehicle "B"	Latency times
CAM published	CAM received	Publication-Reception times
1614257921916	1614257921973	57 ms
1614257922016	1614257922082	66 ms
1614257922116	1614257922173	57 ms
1614257922220	1614257922270	50 ms
1614257922316	1614257922358	42 ms
1614257922416	1614257922466	50 ms
1614257922516	1614257922572	56 ms
1614257922616	1614257922682	66 ms
1614257922716	1614257922775	59 ms
1614257922816	1614257922888	72 ms
1614257922916	1614257922978	62 ms
Publication-Reception average times		**57,91 ms**

Figure 44: Result of latency measurements between the emission of CAM messages from vehicle "A", to reception in vehicle "B" (example with 11 repetitions)

➢ Interoperability tests between Spanish and Portuguese MEC

In these tests, different scenarios have been carried out to verify the communication between MECs and the forwarding of information. It was found that one OBU connected to the MEC of its country publishes messages, and the other OBU connected to the MEC of the other country receives the information correctly. Specifically, these tests have been successfully carried out in two different scenarios, and using CAM messages:

1. The OBU of Spain (connected to the MEC of Spain) publishes a CAM message, and this is received by the OBU of Portugal (connected to the MEC of Portugal).

2. The OBU of Portugal (connected to the MEC of Portugal) publishes a CAM message, and this is received by the OBU of Spain (connected to the MEC of Spain).

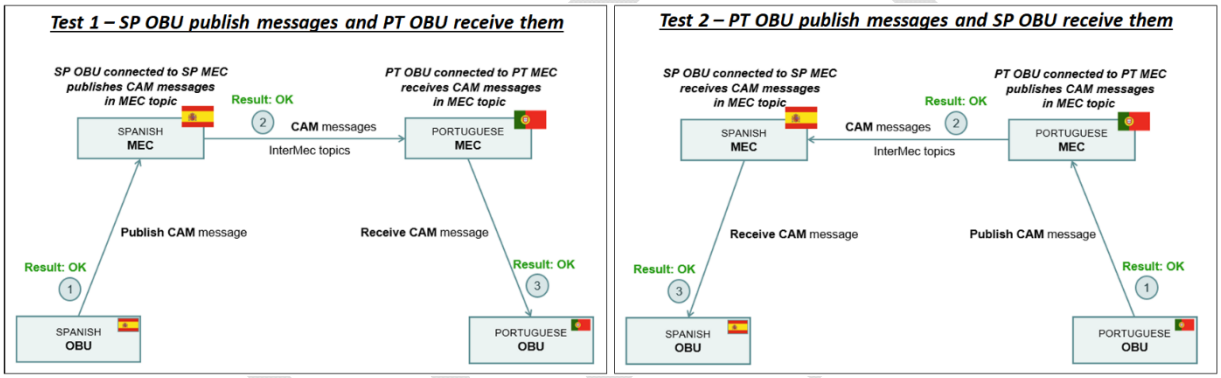

Figure 45: Result of forwarding information between MECs

➢ Testing the processing of received and sent CAM, DENM and CPM messages

In these tests, the operation of the OBU SW was verified when treating the information received and sent through the MEC, as well as the sending through the CAN network of the information received.

The following tests for sending and receiving CAM messages have been successfully performed:

- Publication from the OBU (through the MQTT client) of CAM messages to the MEC, periodically and at intervals of 100ms.
- Correct coding of CAM messages created from the OBU to publish periodically through the MEC.
- Reception at the OBU (through the MQTT client) of CAM messages published by other vehicles, periodically and at intervals of 100m.
- Correct decoding of CAM messages received in the OBU (via the MQTT client).

- Checking the information of the received CAM messages, to verify that malformed messages are not processed.
- Conversion of CAM messages received through the MEC into objects suitable for the vehicle's CAN network.
- Sending the CAM messages received (and transformed to the appropriate format) through the vehicle's CAN network, in the shortest possible time (tests for each use case that uses this type of messages, to verify that the reception and sending times handled along the flow are adequate).
- Checking, for each use case that uses this type of message (CAM), of the receiving and sending times handled along the flow, to verify that they are adequate.

The following tests have been performed to send and receive DENM messages:

- Reception in the OBU (through the MQTT client) of the DENM messages published through the MEC.
- Correct decoding of DENM messages received in the OBU (via the MQTT client).
- Checking the information of the RECEIVED DENM messages, to verify that non-active events are not processed at the present time or malformed.
- Checking the periodic reception at one-second intervals (from the beginning to detect the pedestrian) for the VRU use case.
- Verification of trace analysis of DENM messages received for the HD-Maps use case.
- Conversion of DENM messages received through the MEC into objects suitable for the vehicle's CAN network.
- Sending the DENM messages received (and transformed to the appropriate format) through the VEHICLE's CAN network, in the shortest possible time.
- Checking, for each use case that uses this type of messages, of the reception and sending times handled throughout the flow, to verify that they are adequate.
- Checking, for each use case that uses this type of messages (DENM), of the reception and sending times handled throughout the flow, to verify that they are adequate.

The following tests have been performed to send and receive CPM messages:

- Reception in the OBU (through the MQTT client) of the CPM messages published through the MEC, periodically and at intervals of 100m since there is an object detection.
- Correct decoding of CPM messages (new type of messaging to be treated in the SW) received in the OBU (through the MQTT client).
- Checking the information of the received CPM messages, to verify that malformed objects are not processed.

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- Verification of the correct interpretation of the CPM messages received (through the verification of the positions, and to verify that the data coincide with reality and the vehicles can be positioned correctly from the information received).
- Conversion of CPM messages received through the MEC into one or more objects suitable for the vehicle's CAN network.
- Sending and updating of CPM messages received (and transformed to the appropriate format) through the vehicle's CAN network, in the shortest possible time.
- Checking, for each use case that uses this type of messages (CPM), of the reception and sending times handled throughout the flow, to verify that they are adequate.

In addition to the previous tests, small details have also been checked, such as: the retention of messages until their validity time by the MEC (so that they are received in the corresponding areas from the moment they are first published until they are valid in time), or the periodic emission times to the MEC of cam messages, both on the Spanish and Portuguese sides (to verify that there is not too much time between broadcasts that may cause failures when executing the different use cases).

**NOTE: All these tests were performed first locally and then against the final MEC.*

HD-Maps User Story (simulated)

- Testing HD-Maps scenario processes

In these tests, the trace detection and ADTF parts were simulated to verify the overall operation of the service:

- It was verified that the start and end of the event trace were correctly detected.
- It was verified that the start and end instructions for logging are sent correctly, and that the corresponding confirmations are also received properly.

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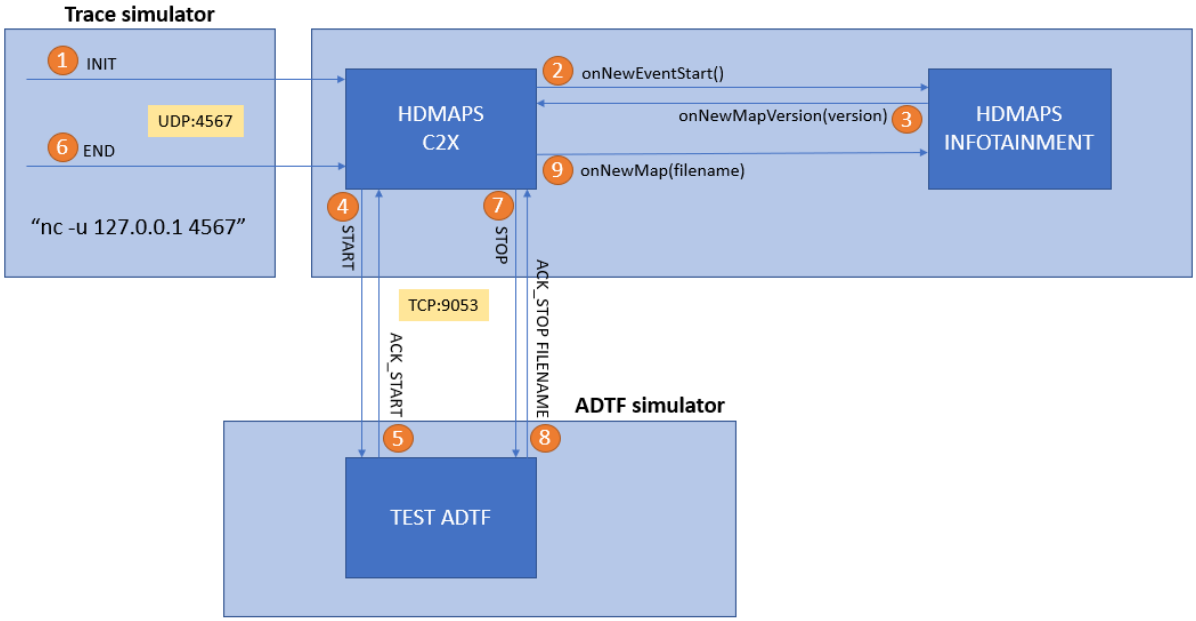

Figure 46: Flow of tests performed to verify the operation of the use case

Logging

- Network analysis of test areas

In these tests, the places of the tests (geographical positions) have been analyzed to verify, in each of them, the type of existing network and their characteristics. In addition, to assign the type of network (and characteristics) to each position, a previously implemented on-board program has been used.

The following Figure 47 is an example of the information that is obtained by this method:

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```
{
    "position": {
        "timestamp": 1592906435000,
        "latitude": 42.102129,
        "longitude": -8.615572,
        "heading": 225.25,
        "speed": 10.25
    },
    "red": "5G",
    "parametrosRed": "",
    "iperf": {
        "start": {
            "connected": [{
                "socket": 4,
                "local_host": "172.19.166.226",
                "local_port": 53178,
                "remote_host": "172.19.166.69",
                "remote_port": 29280,
                "additionalProperties": {}
            }],
            "version": "iperf 3.0.11"
        }
    }
}
```


Figure 47: Outputs of the logging application

- Application layer login testing

these tests aimed to verify that the logging format applied in the sending and receiving of messages complies with the logging specifications defined in the project. Multiple tests were performed to ensure that the timing is accurate enough to be able to reliably track logs. In addition, an auxiliary equipment was added to the internal logging process that allows the sending and storage of logs to it.

Figure 48: CTAG OBU with 5G modem and logging device

- Full communication flow latency analysis

In these tests, V2V network latency measurements were carried out, in order to limit time problems in the different parts of the communication flow. For this, application layer logging was used, as well as network logging.

Specifically, these tests were performed on the CTAG tracks, and the V2V full stream latencies were analyzed for all message types (CAM, DENM and CPM) used in the different use cases.

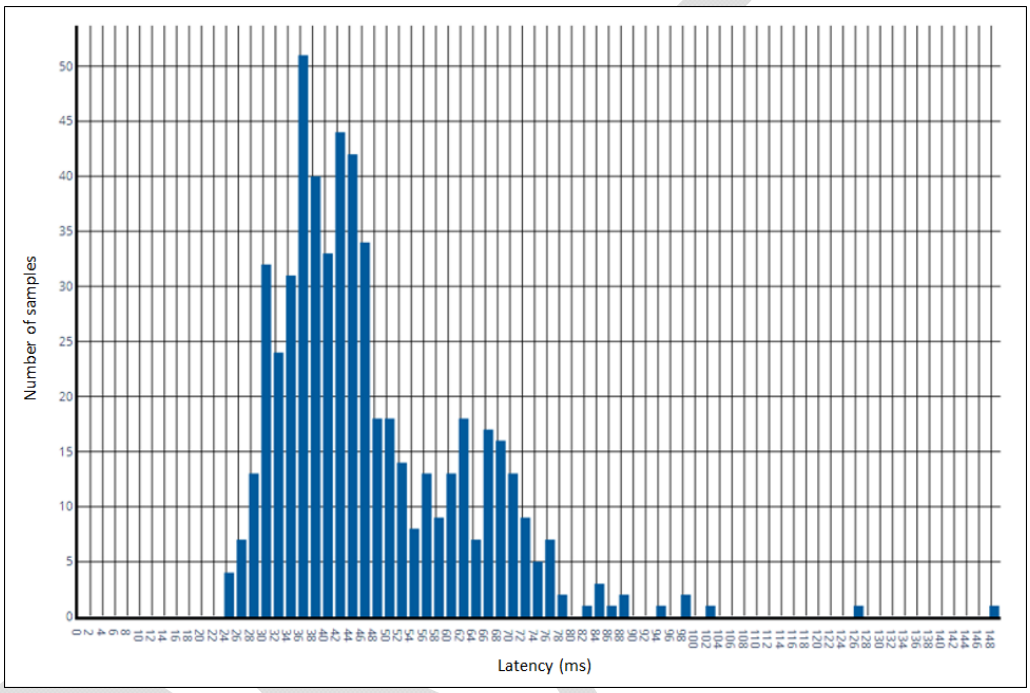

Figure 49: V2V latency analysis result for DENM messages

3.5.1.7. First User Story tests and design conclusions

After having prepared and tested each individual equipment on vehicles, the last stage of the integration and development process involves the whole system testing. The first User Story tests performed with CTAG vehicles have taken place in the CTAG Test Track, which has been adapted for enabling each scenario:

- For the shuttle User Stories, some traffic lights with cameras for detecting Vulnerable Road Users (VRU) have been installed on the test track

Figure 50: VRU tests at CTAG's test track

- Additionally, to support the Remote Driving scenario, all the necessary equipment to control the Shuttle remotely has been installed and configured on the Remote Control Centre.

Figure 51: Remote control cockpit

- For testing the HD Maps User Story, a roadworks scenario was designed and built by using traffic signs and New Jersey blocks, so that the HD map recording, update and download could be tested. Additionally, an Android app was developed out of the scope of the planned developments, to monitor the process steps and the network throughput.

Figure 52: HD Maps tests at CTAG's test track

Figure 53: HD Maps Android app

- For the lane merge scenario, a RADAR sensor connected to the 5G network was installed on the test track, and additionally, a specific lane merge map layout was designed.

Figure 54: Lane merge scenario - Connected RADAR sensor

Figure 55: Lane merge scenario at CTAG's test track

After performing the first tests and analysis of all the User Stories, some design decisions were taken. Next, we summarize them grouped by User Story:

- Automated shuttle in cross-border settings (Cooperative automated operation).

In this scenario the Shuttle will receive the position of a VRU before the onboard sensors can see it. After considering the scenario where the trials will take place, it made sense to place the VRU detector outside of

the bridge, after a 90º turn. On the MIL and HIL tests, the presence of a VRU is simulated, and we can see that the Shuttle anticipates the braking phase to make it more comfortable for the passengers.

- Automated shuttle in cross-border settings (Remote control).

On the remote control scenario, the objective is to detect an object that blocks the path, and that the Shuttle is not able to overtake autonomously. One of the main challenges is to perform the remote control request only when needed and not in some other cases of normal operation that could trigger this. In order to prevent this, a brainstorming session took place to define situations where it does not make sense to request remote control, like for example waiting behind another vehicle on a red traffic light or stop sign, or waiting while a pedestrian is crossing at a crosswalk.

Due to the special architecture of the bridge where the use case will be performed, depending on the time of the day, the sun could generate a shadow pattern that could be very challenging for the artificial vision algorithms. Fortunately, the Shuttle is equipped with different types of sensors which complement each other in order to achieve the expected results.

Furthermore, as the bridge is a narrow road, and the Shuttle is wider than a normal passenger car (width is around 2.4 m), we need to ensure that there is enough space to overtake the obstacle. Several possibilities were studied, like a narrow foam soft target or a pedestrian in the middle of the road. Finally, the decision was to use a cyclist to emulate a real scenario that the shuttle could face on an urban environment.

- Complex manoeuvres in cross-border settings (Lane merge & Automated overtaking).

For the automated overtaking and lane merge User Stories, several scenarios were tested using a driving simulator developed in MATLAB Simulink.

On these simulations we combined the presence of objects generated by ideal sensors (blue boxes) and a noisy copy of those objects (yellow) to simulate C2X objects latency. These tests help to test the sensor fusion layer output (black objects) and also to tune the different parameters that the overtaking and lane merge algorithm uses, like the time gap to the front object, time gap to the rear objects to consider the overtaking manoeuvre safe, time gap of the objects to the lane merge intersection, trajectory generation parameters, etc.

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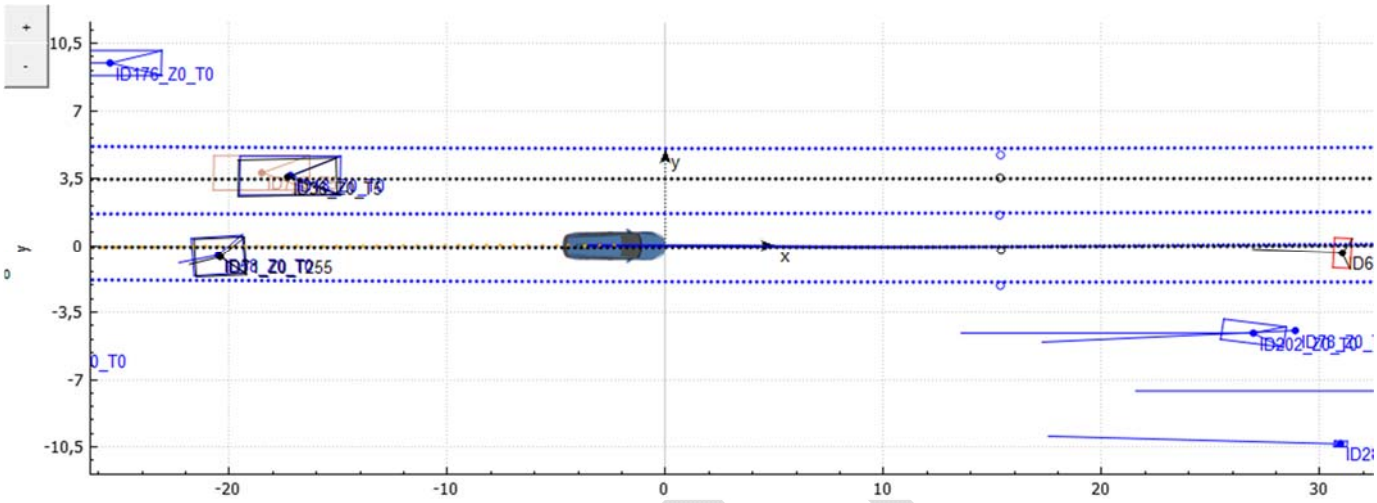

Figure 56: Overtaking simulation

- Complex manoeuvres in cross-border settings (HD maps).

On this use case, the raw data from the vehicle sensors is processed to generate an update on an ADASIS v3 HD Map. This processing could be done in the vehicle or in the cloud. One of the first decisions taken at the start of the development was to do this processing on the cloud. This is due to two reasons. First, because of the high computing power requirements, it makes sense to centralize this processing in a server. This way, data from vehicles with different sensors can be handled on this server to generate a standardized HD Map that could be use by all vehicles. Furthermore, uploading the raw data from the sensors would be more demanding on bandwidth than uploading a processed map, so it made sense to do it this way to stress the network for the tests.

Regarding the processing, two different approaches were discussed at the beginning of the implementation on how to handle the objects on the map. The first approach was to modify the lanes geometry depending on the detected obstacles. The weak point was that, in real life, minor changes in the position of the objects could generate new recordings, as these geometries would change. The second approach was to generate a lane access restriction on the area occupied by the obstacles. Access restriction is supported by the ADASIS standard, so this was the final choice, as it seemed more robust against changes on the scenario.

3.5.2. Nokia and DEKRA early tests

Nokia Bell Labs has taken part in the development process of the Remote Control User Story. Previous to the integration of the equipment in the shuttle and also during the integration and development phase, some different tests were made between Nokia and DEKRA to check potential video transmission issues on the scenario. this section describes some result of these tests and the way how the testing was done.

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Test development

The first integration setup was built with the following two components (Figure 57):

Camera kit:

One Front Camera PTZ for exterior, for **front view (Panasonic WV-X6531n)**
One 360 Camera for exterior, for **360 view (Ricoh Theta V**)

Communication Box

One **small OBU for testing** connectivity built on a **raspberry Pi**, VPN to MEC tests
One **Smartphone with GPS** and connectivity to NSA 3.x in the n78 5G band

Figure 57: Vehicle equipment Installation

Before placing the two cameras in the vehicle several options were studied to understand the quality of the view from both cameras. The two main factors to consider were: The camera Lens Field of View, that was [16:9 mode] Horizontal: 2.1 ° (TELE) – 65 ° (WIDE) for the Front View Camera, while for the 360 Camera it was 360º. And the visual field from the camera to the car perimeter. This measure is very relevant because objects may be outside the field of view due to the position of the camera and, therefore, are not visible.

The 5G radio node is located at about 1.4 km from the test zone and does not have a direct view from the tower antenna. The gain of the antenna for the automotive modem will be critical to have additional dB in the uplink and in the downlink to improve the coverage and the performance of the connectivity. The roof

of the vehicle has a better point of sight for the antennas and there is less car components that can decrease the received signal. Thus, The communication devices were placed in a white box on the roof of vehicle.

During the test some issues with its solutions were found, and they are presented in the following paragraphs.

Radio power in the border by Telefónica

Telefónica has deployed 5G nodes in available sites for 4G, so the antennas location is fixed and the distance to the border (about 1400 meters) is not optimal.. In this case, the impact of this for the cameras is that the video is uploaded at lower speeds, and the required minimum bandwidth was lost many times. This long-distance impacts on downlink capacity, but it is even more remarkable in the uplink. In fact, the 5G NSA 3.x in 3,5 GHz is deployed in TDD with 4:1, so the bandwidth available for uplink is very restrictive. The measures described in this section were obtained with a very preliminary version of the radio software. In newer versions (release 5G19A) throughput behaviour is improved, especially in the upload section.

Figure 58: Line of Sight of Telefónica Antenna

Figure 59 shows a UL Throughput measurement with a boxplot at the left part, and together with signal strength measurements –RSRP and NR-RSRP- at the right part, performed with the DEKRA TACS4 Performance tool at the Spanish side of the crossborder area, driving from the new bridge area to the old bridge area, where the issue of low coverage (RSRP below 100 dBm) is easily visible, and where it is quite clear how the throughput rates decrease together with the signal strength received.

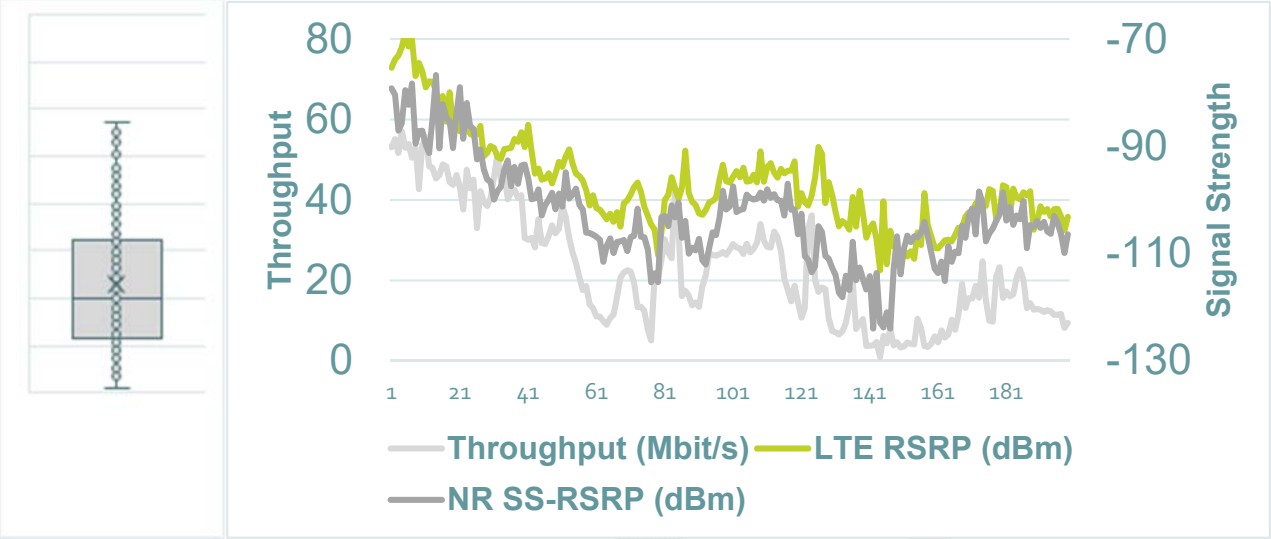

Figure 59: UL Throughput and device signal strength (RSSP) measurement at cross border area

Figure 60, left part, shows the UL throughputs obtained when transmitting UL data simultaneously with 3 devices (User Equipment –UE-), in this case, in the highway close to CTAG facilities. As it can be seen, the behaviour of the 3 devices does not have to be the same when they have to compete between them to obtain network resources. The right part of the figure shows the comparison between the total throughput, sum of the 3 UEs, and the throughput obtained with just one device, when there are no other UEs one requesting the network bandwidth. In both cases, the total throughput provided by the network is quite similar.

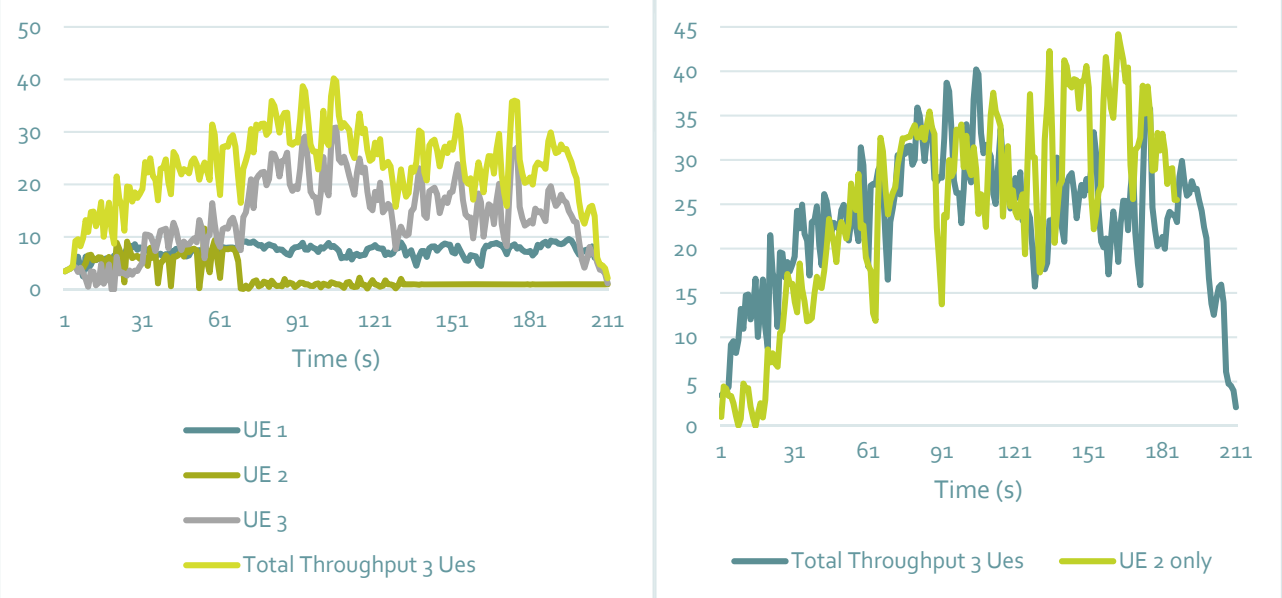

Figure 60: UL Throughput with 3 UEs uploading data simultaneously in Porriño (CTAG) area

The proposed solution was to place the smartphone in the roof of the vehicle as it is shown in the main picture. The camera sensors have been configured to encode video at a maximum of 3 Mbps in AVC, using variable bitrate. In order to have a real correlation of video and bandwidth, these tests are UDP video feeds in the uplink, so the bandwidth limitation in the captured video can be captured and analysed.

Video Traffic test

Video was uploaded in UDP, so one missing UDP packet has an impact on quality. At these bitrates, missing an UDP packet of 150 bytes has a ¼ probability of visual impact, but since many UDP packets can be lost, the impact in the quality of the video is very high. In Figure 61 can be seen how the video quality is good at the Portuguese side of the bridge:

Figure 61: Inside the Bridge Video Capture

However, as the vehicle is driven to the Spanish side of the bridge, the radio signal gets weaker and some packets are lost with an initial small impact on the video frames (Figure 62).

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Figure 62: Inside the Bridge Video Degradation I

The solution in the border of the bridge, where the quality of the 5G Telefónica network is very limited, is that NOS will deploy a radio antenna just in the border of the bridge, so it is expected that in case the quality in Telefónica network is not good, the vehicle can switch to the NOS network in the area. The other solution is to decrease the required camera bitrate in order to deliver the video without loss of packets. If the video is LOW LATENCY VIDEO, the delivery of UDP is almost mandatory to save time in the video delivery. There are other retransmission techniques for UDP reliable traffic, but these options increase the frames latency, so are not considered by now. Other option is to deliver video using TCP but, in this case, there is a relevant impact on delay. The most efficient method is UDP delivery.

The border area of the old bridge was initially split into 3 zones:

- Area 1 – Good NOS Radio 5G/4G Coverage
- Area 2 - Good TEF Radio 5G/4G Coverage
- Area 3 - Medium to Low TEF/NOS Radio 5G/4G Coverage

The idea is that dedicated small cells of NOS provided the third area with good coverage but at the same time not invading (in terms of radiation) the Area 2. The changes will be tested in the handover scenarios.

Missing coverage with metallic trucks overtaking

During the recordings in the highway, when a big truck with metallic load overtook the vehicle, some video effect was perceived due to missing UDP packets. This spurious lack of radio quality shows that having only one radio feed from one single site in the motorway makes the real-time video feed extremely vulnerable to clean radio links to the automotive antenna.

The solution to provide continuous video feed will be always to have more than one site connected to the car with carrier aggregation.

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Speed impact on the video quality

The cameras have been fine-tuned to provide good video quality in interiors and exteriors, but when the camera is mounted in the vehicle, and it starts to move, the video quality was degraded. The low latency configuration of the camera requires not using B frames in order to save PTS/DTS times and keep the video latency under minimum values. This means there is a trade-off between low latency and used bandwidth when performing such GOP (Group ff Pictures) encoding schemas.

The solution for this is to only use Low Latency Video in video configuration that requires Low Latency like remote driving control. In the case of remote driving, it is recommended to use as much as possible bandwidth in order to guarantee the required minimum video quality. In the areas where remote driving is required, it is better to have a very good uplink channel.

Loosing minimal radio signal many times in the bridge

In the bridge area, and sometimes in other areas with low quality coverage has been observed that the 4G carrier is constantly leaping from side to side, causing additional throughput degradation. Some of the 4G carriers are located at very long distances, providing very low uplink throughputs. In Figure 63, we can see that the 4G node changed 8 times. In some of these occasions the nodes did not have 5G carrier signal capacity. The 4G nodes that have direct view at very long distance are covering the old bridge area and are used by the smartphone if the nearest node is out of sight. Therefore, there are some issues: there is no 5G coverage, the 4G node has no capacity and the performance of the uplink channel to nodes located at almost 6 km in the 2600 MHz band is extremely low.

The solution is to use a non-commercial PLMN SIM that is only associated to the 4G nodes where we have 5G capacity. Other option is to control in the automotive modem when the modem must handover from a 4G node to a different node, avoiding Ping-Pong cases.

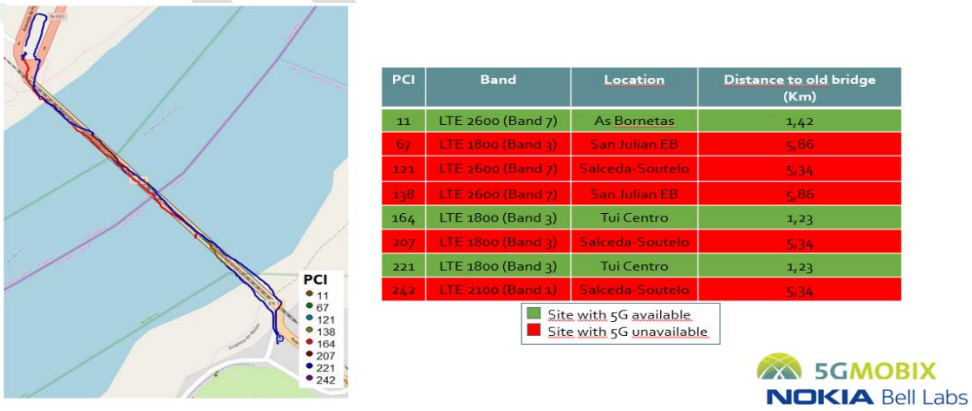

Figure 63: Antenna Position Analysis

After several tests the following table represents the TACs and PCIs configured for the scenario:

Sector	Global Cell ID	Cell Name	Physical layer cell ID	EUTRAN Cell ID	TAC	Band		EARFCN downlink	EARFCN uplink	PLMN
1	10	TUI_CENTRO_360091801_010	55	92198410	36601	3 (1800+)	20 MHz	1301	19301	21438
	11	TUI_CENTRO_360091801_011	76	92198411	36601	20 (800 DD)	10 MHz	6400	24400	21438
	12	TUI_CENTRO_360091801_012	228	92198412	36601	7 (2600)	20 MHz	2850	20850	21438
	14	TUI_CENTRO_360091801_014	136	92198414	36601	1 (2100)	10 MHz	550	18550	21438
2	20	TUI_CENTRO_360091801_020	221	92198420	36601	3 (1800+)	20 MHz	1301	19301	21438
	21	TUI_CENTRO_360091801_021	42	92198421	36601	20 (800 DD)	10 MHz	6400	24400	21438
	22	TUI_CENTRO_360091801_022	100	92198422	36601	7 (2600)	20 MHz	2850	20850	21438
	24	TUI_CENTRO_360091801_024	164	92198424	36601	1 (2100)	10 MHz	550	18550	21438
3	30	TUI_CENTRO_360091801_030	78	92198430	36601	3 (1800+)	20 MHz	1301	19301	21438
	31	TUI_CENTRO_360091801_031	44	92198431	36601	20 (800 DD)	10 MHz	6400	24400	21438
	32	TUI_CENTRO_360091801_032	62	92198432	36601	7 (2600)	20 MHz	2850	20850	21438
	34	TUI_CENTRO_360091801_034	153	92198434	36601	1 (2100)	10 MHz	550	18550	21438

Sector	Global Cell ID	Cell Name	Physical layer cell ID	NR Cell ID	TAC	Band		NRARFCN	Icrid	PLMN
1	1	TUI_CENTRO_3600918680101	445	5898354689	36601	n78	40 MHz	651666	1	21438
2	2	TUI_CENTRO_3600918680102	446	5898354690		n78	40 MHz	651666	2	21438
3	3	TUI_CENTRO_3600918680103	447	5898354691		n78	40 MHz	651666	3	21438

Figure 64: TACs and PCIs of LTE Anchoring Cells

Several agnostic tests were executed in the Old Bridge and New Bridge areas in order to be able to have an overall view of how much traffic and an estimation of the latencies in this zone. The results have been obtained in JSON format and exported to CSV. The process is as follows:

1. Each agnostic test encoded as the executed Agnostic code
2. Same script must run on the MEC and in the UE MCU
3. Tests script results are generated at both ends, stored in json format
4. Additional results are recorded in some tests with Keysight Outdoor
5. Automatically tests reports are generated with graphics and are sent in real time to programmed email addresses
6. Finally, the results json logs are postprocessed to the common results data format

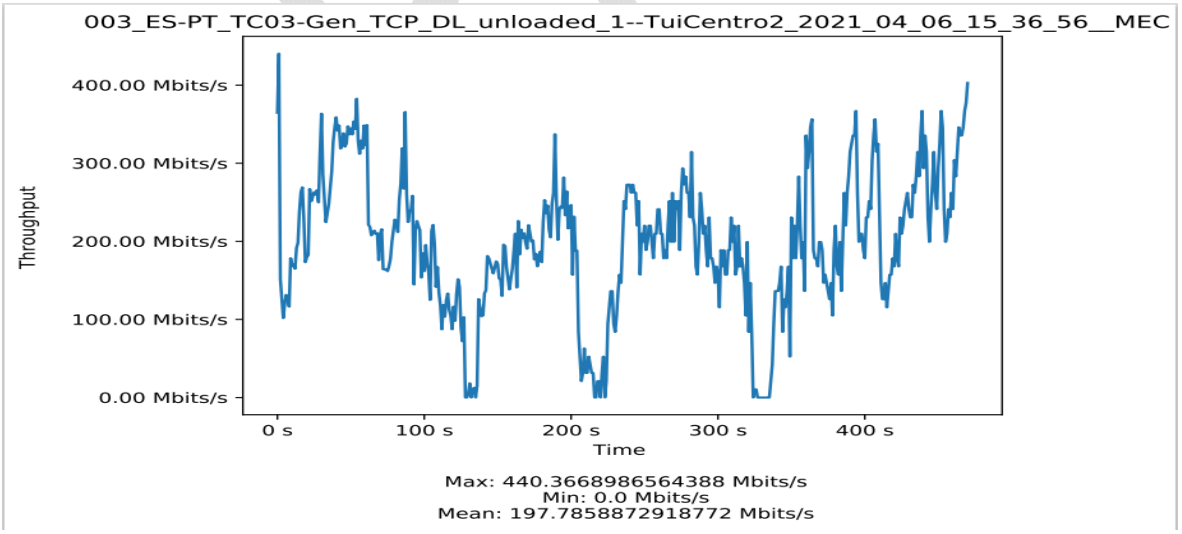

Figure 65: Sample of Agnostic Test Generated Measurement

Additionally, some outdoor traces have been captured so that detailed radio protocol information is available for all measurements. This a have low level Qualcomm traces details on the UE.

VR360 view for outside view of the car may not be enough

The 360 camera in the top of the car provides a very good view of the area around the vehicle, but shows some disadvantages like missing lot of bits in the top and the bottom view (in the top the sky is visible, while in the bottom the vehicle roof is shown). Also, there is not a clean view of the perimeter of the vehicle. Therefore, while the 360 camera offers a broad view of the vehicle's surroundings, it may not be the best approach in some cases where the bandwidth is critical, or the remote vehicle driving perimeter view is mandatory. In the following 360 photograms (Figure 66 and Figure 67), we have the 360 view and in red colour the areas of no interest for the remote driving case.

Figure 66: 360 Video Sectors Optimization

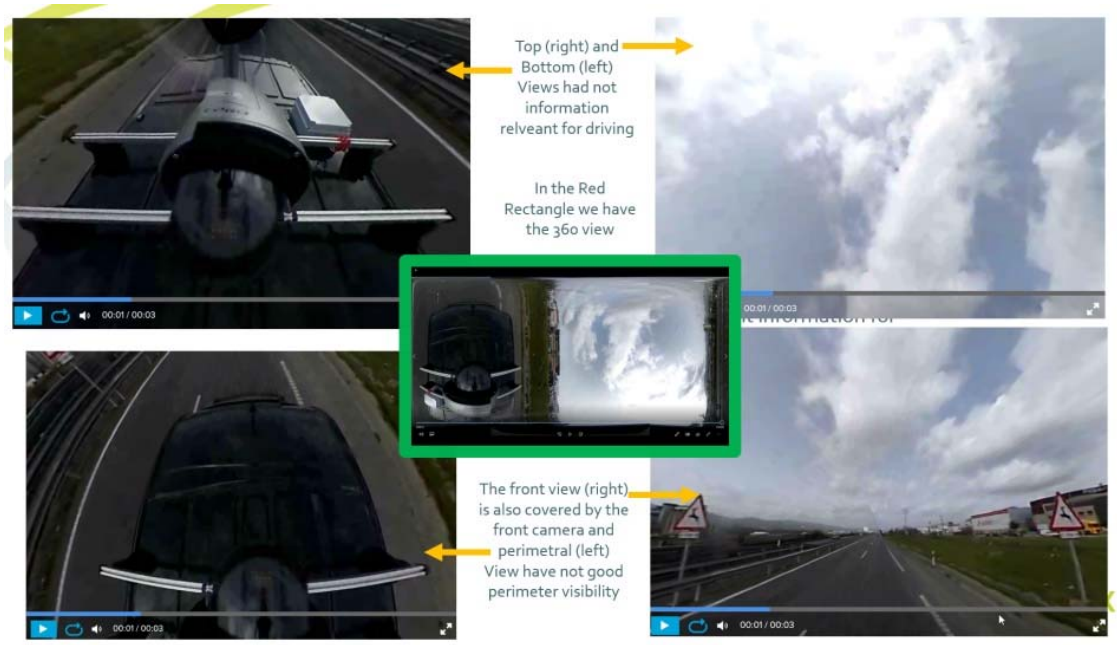

Figure 67: Non 360 Cameras Optimization

The Solution to optimize the information per pixel and then the bandwidth for the uplink is to place several cameras without 360 view that can include more relevant information of the perimeter of the vehicle. These cameras could have smaller resolution in order to consume less bandwidth, and optionally, depending on the car manoeuvre, the bitrate of the perimeter cameras may be increased when needed.

Finally, four cameras with full HD resolution (1920x1080p) have been installed in the vehicle. They transmit video via UDP. The final stitching is performed in a VR Unity Application which incorporates a 3D synthetic model of the vehicle mixed with the 4 video streams coming from the cameras.

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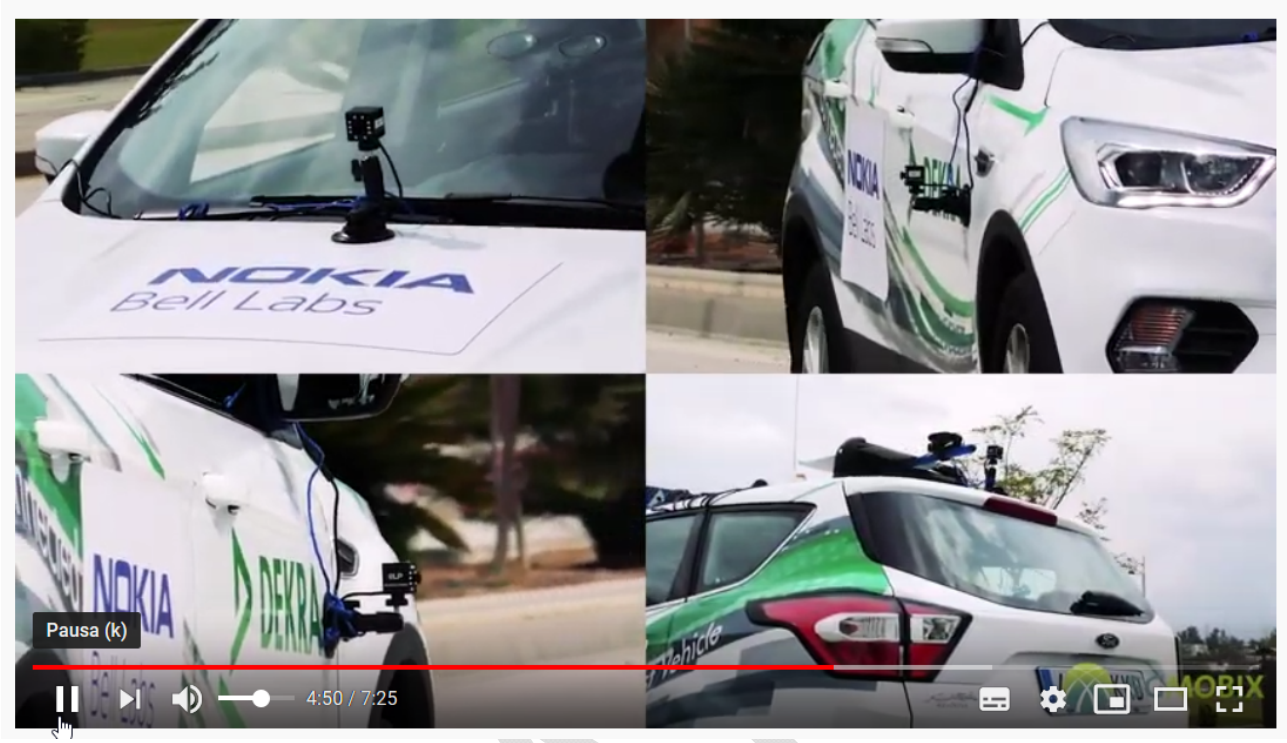

Figure 68: Remote driving cameras located in a test vehicle

three cameras cover an area slightly bigger than 180 degrees in the front part and a rear camera which is projected into a virtual rear mirror, located in the usual place for such mirrors in real vehicles.

Bitrates are initially adjusted at 4MBps per camera, except for the rear one which is started at 3Mpbs as the resolution of the area into which the video is rendered is smaller than the rest of Unity surfaces.

Real-time video encoding is performed in a Jetson Xavier NX board which has four hardware H.264 video encoders which are optimized in order to receive low latency M-JPEG flows from the cameras and then reencoded int UDP video with a minimum jitter buffer of 10ms. Gstreamer pipelines have been also customized so that it is possible to retrieve encoding stats at a given point in time.

An example of the parameters being used in transmission by one of the cameras is this one:

```
/usr/bin/gst-launch-1.0 -v v4l2src device=/dev/video0 do-timestamp=true !
image/jpeg,width=1920,height=1080,framerate=30/1 ! jpegdec ! nvvidconv ! nvv4l2h264enc
iframeinterval=30 bitrate=4000000 insert-sps-pps=1 ! video/x-h264, stream-
format=(string)byte-stream ! rtph264pay mtu=1200 ! udpsink max-bitrate=4000000
host=10.8.1.10 auto-multicast=true port=3001
```

The developed control protocol application receives telemetry data from the vehicle, which is directly forwarded to another UDP local port to the Unity application which is running in the same PC. This is in turn directly connected to the HMD device using a high-speed USB-C cable. Finally, all the telemetry is rendered

in the UI application, including items such as the actual speed of the vehicle, the GPS position and the RTT latency of the control commands with levels of colours (green, yellow and red) for the different ranges. The movement of the wheel is transmitted from the local Logitech Device which is connected to the same PC.

The mixed view of the reality in the vehicle which is rendered on the HMD device can be seen in the pictures above.

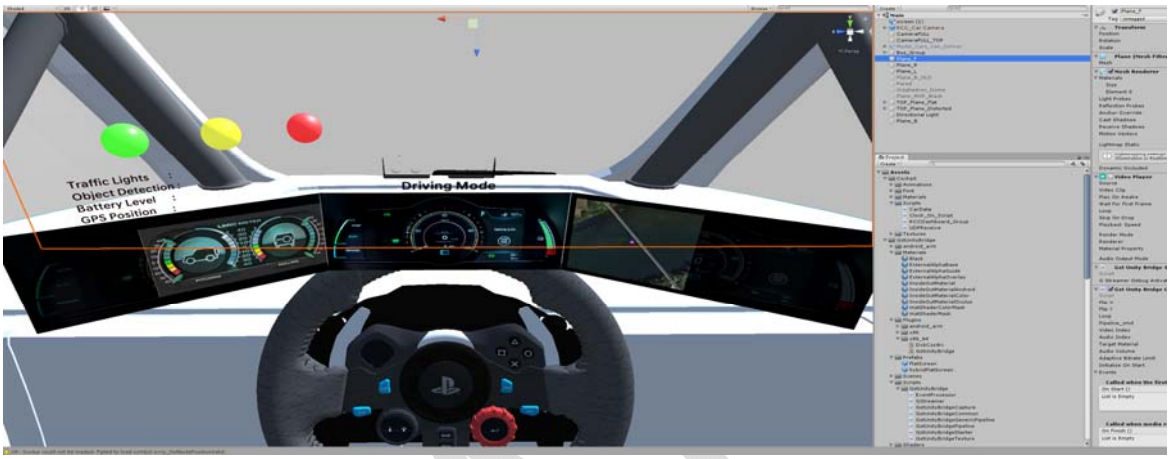

Figure 69: Cockpit VR Unity Project

Figure 70: Cockpit VR Execution with Real Video Contributions

3.5.3. IT early tests

Preliminary latency tests

Some firsts tests were performed to analyse the 5G connectivity in vehicles' OBUs, observing the uplink and downlink latencies at the application layer, which also include the communications and message handling services running in the OBU. These preliminary tests allowed the verification of valid 5G network connectivity status, existing MEC broker connection for message exchange and correct publication/subscription to the MQTT topics. Figure 71 shows the obtained latencies values during a 2 minutes' test, when the PT connected vehicle's OBU was connected to the 5G Portuguese network in the border, publishing CAM packets to the MEC MQTT broker and subscribing them back, in order to measure the observed end-to-end and intermediate delay values.

Figure 71: Preliminary 5G latency test with the PT Connected Vehicle

4. VEHICLE INTEGRATION OF GR-TR CBC

The GR-TR trials will take place using a FORD truck with autonomous driving/platooning capabilities. Details of FORD Truck can be found in section 4.2. In order to realize all four User Stories of the GR-TR corridor, different OBUs and automated driving functionalities have been developed by the GR-TR partners, while different sets of onboard (and road-side) sensors are also utilized. The developed OBUs and sensors have been integrated with the FORD truck in order to allow the various functionalities of the GR-TR User Stories. Table 5 below provides an overview of the various vehicle related equipment developed for the GR-TR trial, while details regarding their design, development and testing are provided in the following sub-sections. It has to be noted that different RSI, road-side sensors and applications have also been developed for each of the User stories, but they are presented in deliverable D3.4 (5). of 5G-MOBIX.

Table 5: Overview of OBUs, driving functions and sensors utilized in the GR-TR CBC

User Story (US)	US Lead partner	On-Board Unit	Sensors	Driving function
US 2.1.a Platooning with "see what I see" functionality in cross-border settings	ICCS/ AALTO	IMEC OBU	RTK-GNSS, Camera, RADAR, Webcam	Platoon Manoeuvres (Join, Dissolve, Merge, Split, Maintain) See Through
US 2.1.b Platooning through 5G connectivity	FORD	IMEC OBU	RTK-GNSS, Camera, RADAR	5G Platooning Manoeuvres (Join, Dissolve, Merge, Split, Maintain)
US 3.2.a Extended sensors for assisted border-crossing	WINGS	WINGS OBU	Proximity, CO_2, NFC, GPS	Customs agent protection (autonomous braking, Threat assessment of incoming trucks)
US 3.2.bTruck routing in customs site	TUBITAK	IMEC OBU	VLP-32 LiDAR	X-ray Inspection, Autonomous Path Following

4.1. Sensors & devices integration

Table 6: GR-TR vehicle sensor information

Type of Sensor	Units	Characteristics	Additional info
Camera	2	• 4K Ultra HD video streaming • Mobileye 630	• Ensures the high quality video transfer between the leader and the following vehicles • Placed on windshield , FOV:30, Range: 60m (car) 40 m (ped.). It is used at Platooning use case for vehicle perception
RADAR	1	• Continental ARS408 Long Range	• Located on the front grille, Range:200m. It is used at Platooning use case for vehicle perception
GNSS	1	• Novatel OEM7 Series	• Precise positioning up to 1 cm with RTK capability. It is used at Platooning and Autonomous Truck Routing User Stories.
Inertial	1	• Epson G320N MEMS IMU	• Included in GNSS product. Low noise commercial grade Gyros and Accelerometers
Odometer	1	• Stoneridge Tachograph	• Provides precise and regulatory vehicle speed and odometer
Steering sensor	1	• Bosch ServoTwin	• Electro-hydraulic steering capability
PC	1	• dSPACE MicroAutoBox II	• IBM PPC 750GL, 900 MHz (incl. 1 MB level 2 cache). 16 MB main memory.16 MB memory exclusively for communication between MicroAutoBox and PC/notebook.16 MB nonvolatile flash memory containing code section and flight data recorder.

			Clock/calendar function for time-stamping flight recorder data. 4 CAN channels. 2 x RS232 interface. 2 x serial interface usable as K/L-Line or LIN interface. 100/1000 Mbit/s Ethernet connection (UDP/IPTCP/IP on request). RTI Ethernet (UDP) Blockset (optional) for read/write access. LEMO connector.
Communication	IMEC OBU	5G connectivity C-V2X PC5 short range Routing of data over 5G and C-V2X PC5 Manages the connectivity and data streams from the Ford MABX to the application servers	IMEC OBU can manage the complexity of handling both the 5G connection and C-V2X PC5 connection for the different use cases. It provides an intermediate gateway between the Ford MABX and application servers and offers abstraction to the Ford MABX regarding the communication towards these application servers.

4.1.1. Platooning with "see-what-I-see" functionality equipment & sensors

In this project, two FORD F-MAX trucks will be used. These trucks will be equipped with front RADAR and front camera for object detection, electronic steering wheel controller, RTK-GNSS for cm precise positioning, rapid prototyping unit for vehicle autonomous controller (dSpace MicroAutoBox II), and IMEC/WINGS on-board unit for connectivity.

Additionally, LEVIS clients (for video encoding, decoding) and one 4K camera (only for front vehicle) will be used for "See What I See" video streaming application. The High level vehicle architecture can be seen on Figure 72 below.

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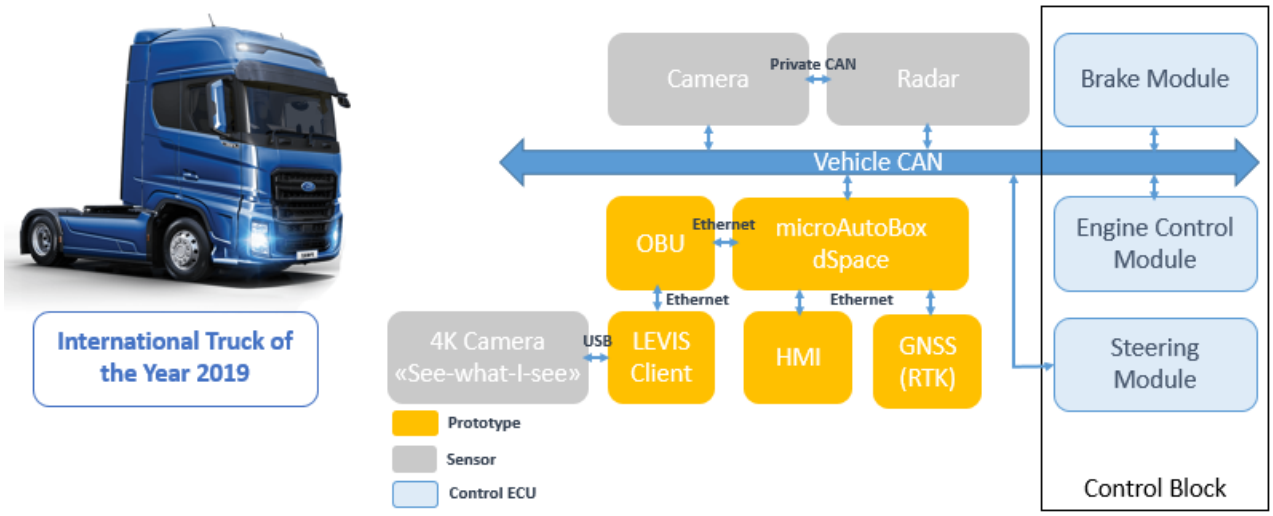

Figure 72: High Level Hardware Architecture of F-MAX Trucks

FORD OTOSAN works on vehicle controller algorithms and for this purpose the dSpace MicroAutoBox II (MABX) module is used. MABX is a fast prototyping module. Algorithms are developed first on MATLAB and after that, they are integrated into MABX module. For this project dSpace MicroAutoBox II[3], DS1401/1513 will be used. Picture of the module can be seen on Figure 73 below.

Figure 73: dSpace MicroAutoBox II – 1401/1513

[3] https://www.dspace.com/shared/data/pdf/2020/dSPACE-MicroAutoBoxII_Product-Brochure_2020-02_EN.pdf

To accomplish platooning, RADAR, camera and GNSS information are the required sensor suits. This sensor suits provide perception and with the help of this perception vehicle controllers are manipulated with software. For RADAR, Continental ARS408[4] is usedFigure 74 ().

Figure 74: Continental ARS408 RADAR

As camera suit, Mobileye 630 Series[5] and Logitech 4K Brio Stream are used. Pictures of the sensor can be seen below (Figure 75). More detail is also can also be found in the product website:

Figure 75: Mobileye 630 Series (on left) and Logitech 4K Brio Stream (on right) Camera

For US 2.1.b Platooning through 5G connectivity, same equipment will be used in vehicles.

[4] https://conti-engineering.com/components/ars-408/

[5] https://www.mobileye.com/us/fleets/products/mobileye-6-collision-avoidance-system/

4.1.2. Assisted "zero-touch" border crossing equipment & sensors

In order to realize the "Assisted zero-touch border-crossing" User Story at the GR-TR the following equipment are deployed by WINGS inside the FORD truck.

- 1 integrated portable OBU installed in the FORD Truck (connection with the truck's ECU to receive data regarding speed, revs, etc.). See Section 4.3.2 for detailed information on the WINGS OBU.
- Multiple sensors connected via cable to the OBU measuring a multitude of metrics from the cargo haul and around the truck, namely:

CO2 sensor: For CO_2 level measurements, the CCS811 sensor from Adafruit is used. The sensor's output range is [400 – 8192] ppm. A connection to the OBU is established through the I2c protocol.

Proximity sensor: The LiDAR lite v3HP is attached in the middle of the front bumper of the vehicle and it measures the distance from the vehicle in front, or a possible obstacle/human. The sensor has a range of [0.05m – 40m], operates at 5V DC power supply. it can sample faster at rates greater than 1kHz (necessary for the URLLC functionality of VRU protection) and still possesses an accuracy of +/- 2.5cm at >2m. The sensor is housed in a durable, IPX7-rated housing that makes it water resistant. A connection to the OBU is established through the I2c protocol.

NFC (reader & tags): The ACR122U NFC Reader is a PC-linked contactless smart card reader/writer based on 13.56 MHz Contactless (RFID) Technology. Compliant with the ISO/IEC18092 standard for Near Field Communication (NFC), it supports both MIFARE and ISO 14443 A and B cards and tags. Every time that a cargo NFC tag is scanned, its ID is added on a list of ID's of contained cargo. Each ID is removed from the list when the corresponding cargo is exported. A connection to the OBU is established via a USB port

GPS (GNSS) module: Global Navigation Satellite System (GNSS) services are provided by the SIM7600 with the following specifications:

- Receiver type: 16-channel, C/A code
- Sensitivity: Tracking: -159 dBm (GPS) / -158 dBm (GLONASS) / TBD (BD), Cold starts: -148 dBm
- Time-To-First-Fix (open air): Cold starts: <35s, Hot starts: <1s
- Accuracy: Position: <2.5 m CEP

As the GPS positioning accuracy obtained by the on-board GNSS module is not fine-grained enough to support the customs agent protection scenario, WINGS has implemented a two-factor positioning verification system, to ensure the customs agent's safety (VRU protection). The distances between the incoming trucks and all customs' agents are constantly calculated based on their GPS signals. If that distance is decreasing, indicating that a truck is coming closer to an agent, then the readings of the on-board proximity sensor are also consulted. If both the calculated distance based on GPS and the proximity sensor readings indicate that a collision among the truck and a custom agent is imminent, then an autonomous braking instruction is issued to the truck, which immediately brakes to avoid the accident. URLLC communication is necessary for the transmission of GPS and proximity sensor measurements, as well as for the transmission of the braking command to the truck.

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4.1.3. Truck routing in customs site equipment & sensors

In addition to the sensors and devices described in the sub-section 4.1.1.for Autonomous Truck Routing Application at Ipsala Border Area, precise positioning is needed to follow paths that are sent by TÜBİTAK cloud. Precise positioning will be accomplished by using Oxts RT-3000 v2 (Figure 76) and with and NTRIP (Network Transport of RTCM data over IP) connectivity. NTRIP Server will be provided by TUSAGA-Aktif[6] and NTRIP Client will be Lefebure[7] opensource software. With this setup, a precision 9cm precise positioning was shown in figure Figure 77 below:

Figure 76: Oxts RT-3000 v2 for RTK-GNSS precise Positioning

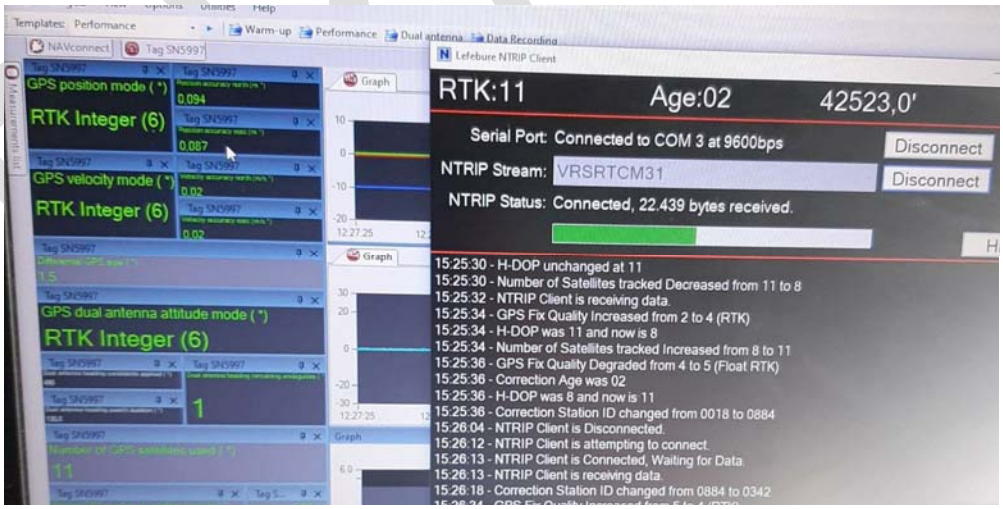

Figure 77: Lefebure Client and Oxts RT 3000v2 position information

[6] https://www.harita.gov.tr/english/u-13-turkish-national-permanent-rtk-network--cors-tr-tusaga-aktif-.html
[7] http://lefebure.com/software/ntripclient/

4.2. Automated driving function development

4.2.1. Platooning with "see-what-I-see" functionality

As mentioned in sub-section 4.1.1 FORD OTOSAN also works on vehicle controller algorithms and they are mainly listed below:

- Platooning controller algorithms (e.g. join, split, merge, maintain, dissolve etc.)
- RADAR – Camera multi object tracking algorithm for perception
- Waypoint tracking algorithm for Autonomous Truck Routing Application.
- CAN (Controlled Area Network) to Ethernet and Ethernet to CAN message gateway algorithms

Algorithms are developed first on MATLAB and after that, they are integrated into MABX module. Main development blocks that are accomplished on MATLAB – Simulink and integrated into MABX can be seen on Figure 78 below:

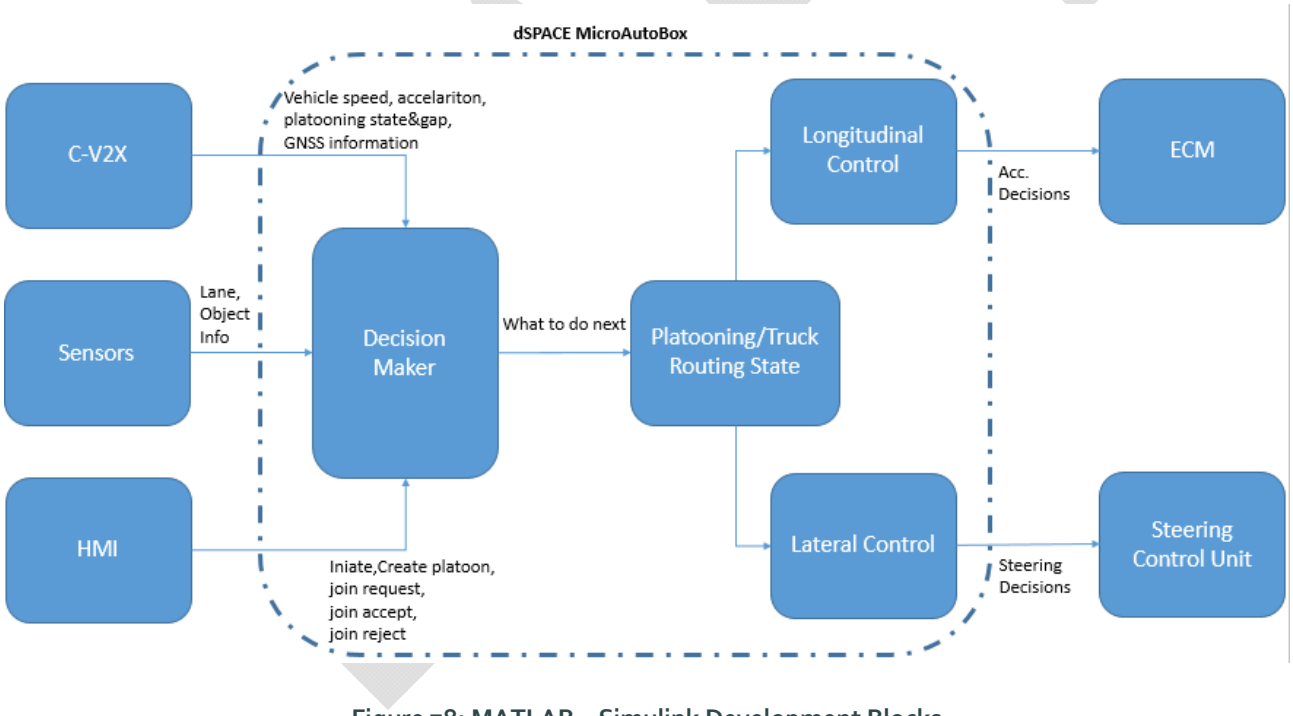

Figure 78: MATLAB – Simulink Development Blocks

Decision Maker gathers sensor, C-V2X data and HMI input and decided to control vehicle for either the Platooning application or the Autonomous Truck Routing application. After that decision is made, required longitudinal and lateral controller algorithms that are developed by FORD OTOSAN take action to drive vehicle autonomously. ECM (Engine Control Unit) is manipulated for acceleration/deceleration and Steering Control Unit is manipulated for directional decisions.

4.2.2. Assisted "zero-touch" border crossing functionality

The full functionality of the WINGS Assisted "zero-touch" border-crossing platform is described in deliverable D3.4 (5), where the 5G-MOBIX application are presented. However we will point out in this section the autonomous driving functionality enabled by the WINGS platform and OBU. Based on the information transmitted by the integrated sensors through the WINGS OBU two different autonomous driving functionalities are enabled:

- ***Autonomous braking for customs agent's protection***: Upon the detection of a customs agent in close proximity to the truck (based on GPS distance + proximity sensor reading) an autonomous braking order is issued from the WINGS platform and the FORD truck immediately breaks to avoid the accident in the customs area.
- ***Autonomous driving to the appropriate inspection lane***: Based on the input collected by the on-board and road-side sensors the WINGS platform performs a threat assessment classification for each incoming truck. Based on the outcome of this threat assessment trucks are expected to go through a more rigorous manual inspection by customs agents (high risk assessment), a more light-weight inspection (medium risk assessment) or even no further inspection (low risk assessment – zero-touch border crossing case). Depending on the outcome, the risk is evaluated and the truck may be instructed to autonomously drive to a respective lane within the customs. This functionality is enabled by the *truck routing in customs site* User Story.

4.2.3. Truck routing in customs site functionality

The algorithms implemented for this Use case are listed in sub-section 4.2.1.

Both lateral and longitudinal controllers are verified by unit testing. Path following performance of the pure pursuit lateral controller is shown in Figure 79 below. Here, the reference way points are generated according to actual geometry of Greece-Turkey border side roads. At the bottom plot, black dots represent reference way points and red line show actual truck position in local cartesian coordinates. At the top plot, red line denotes path following error in meters and dashed black line stands for the error bound with 0.50 m. As can be observed from Figure 79, reference way points are followed accurately. The algorithm detects the corresponding way point at a look ahead distance away from rear axle centre, then the steering wheel angle is computed.

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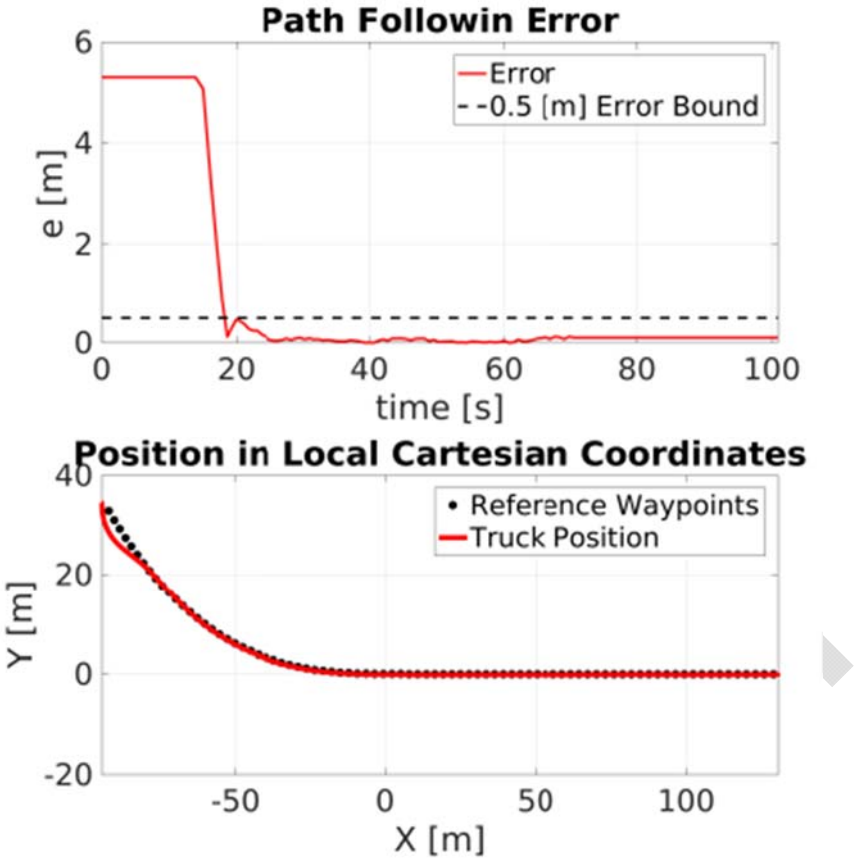

Figure 79: Lateral controller performance in terms of path following accuracy

Since the truck is initiated outside of reference way points, path following error starts at 5.303 m. However, it is apparently seen that path following error is reduced below 0.50 and 0.25 meter bounds, respectively. Common width of any lane is 3.5 meter. The test truck has 2.5 meter width. Therefore, 0.50 meter is maximum available path following error without violating its lane. The lateral controller satisfies the requirement with keeping path following error below 0.25 meter along the reference way points. Speed tracking performance of the cascaded longitudinal controller is shown by Figure 80Figure 78.

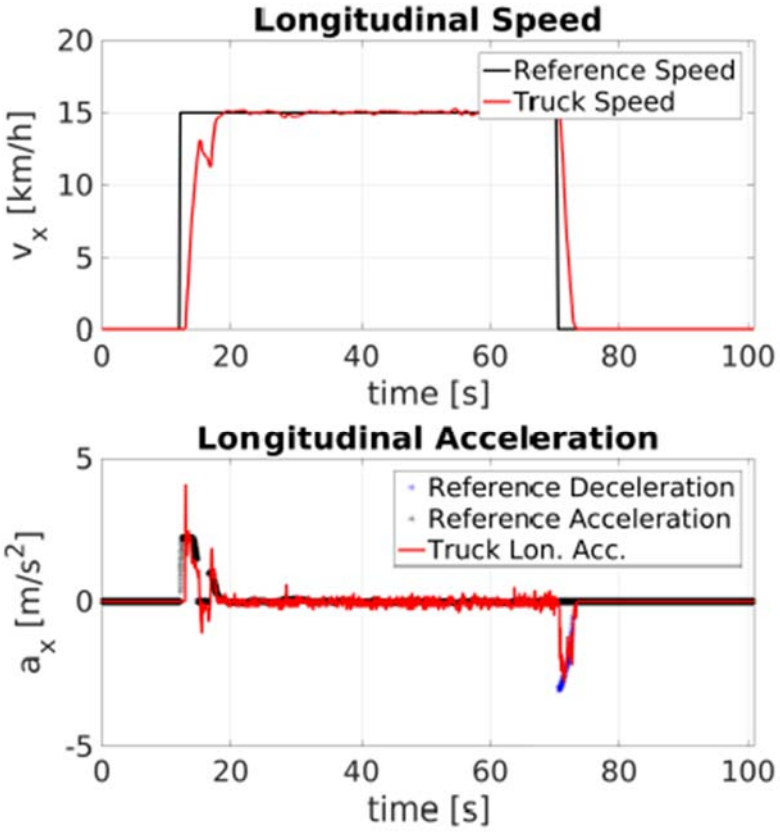

Figure 80: Longitudinal controller performance in terms of reference speed tracking and acceleration/deceleration tracking

At the top plot, black line represents reference speed value, red line represents actual truck speed. At the bottom plot, black dots denote reference acceleration, blue dots denote reference deceleration and red line stands for actual longitudinal acceleration of the Truck. It is apparently seen that reference speed value 15 [kph] is successfully reached by cascaded longitudinal controller. There is a small temporarily oscillated response around 11 [kph] due to gear shift process. The small transient oscillation in the truck speed response is occurred due to the rapid decrease in reference acceleration value shown in bottom plot. The reference acceleration value is set to zero during gear shift, since acceleration tracking performance of any longitudinal controller can not be guaranteed during gear shift. When the reference speed value suddenly decreased to zero as shown in top plot, it is observed that reference deceleration value is reached approximately −3 [m/s2]. Tracking reference deceleration value is achieved by EBS system as can be seen from bottom plot. Then the truck speed is quickly converged to zero and standstill state is reached.

Path following performance from field tests with Tübitak Cloud can be seen from Figure 81.

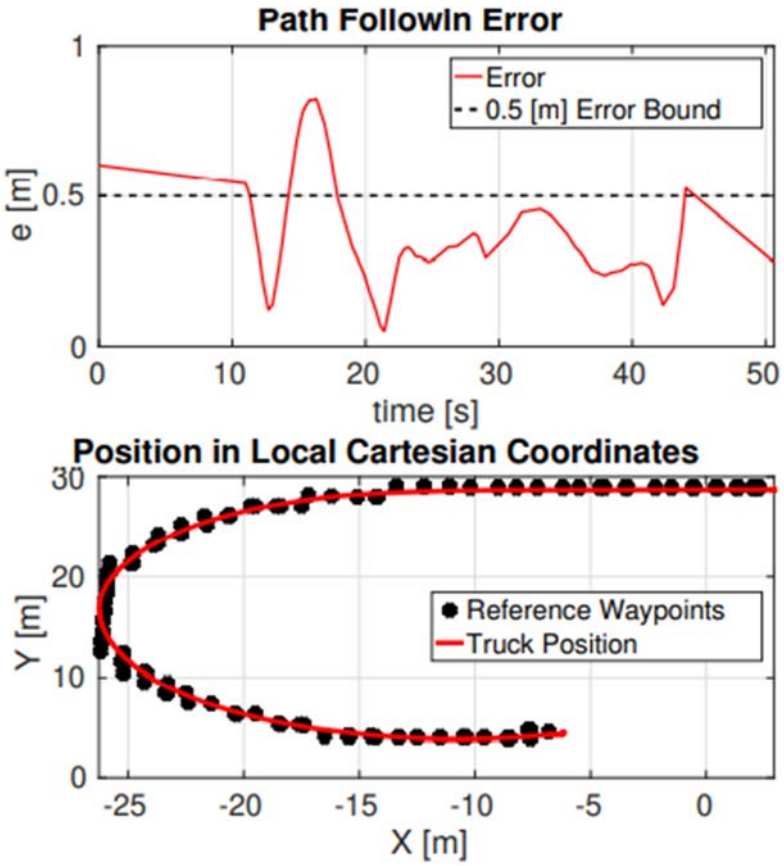

Figure 81: Integrated test results of lateral controller with cloud based path planning

It was previously shown that the designed lateral controller is capable of sufficiently accurate reference tracking in Figure 79. As can be seen from Figure 81, the integrated test results are slightly worse in terms of path following accuracy. The maximum allowable path following error bound 0.50 meters is violated at the beginning and the bound with 0.25 meter is violated three times. However, it cannot be concluded that the path following performance is drastically decreased. In the unit tests, reference way points are held constant and time invariant. In the integrated tests, the reference way points are generated dynamically according to Dijkstra algorithm. It is observed that reference way points are not smoothly curved in integrated testing scenario.

In Figure 82, curvature for reference way points and truck positions are provided for both testing scenarios. Curvature profile is changing discontinuously in integrated testing. Path following error is increased above boundary values whenever the curvature changed significantly. Despite the fact that the path following error is larger, the truck is moving with quite smooth curvature. In Figure 81, it is shown that the truck position removes oscillatory characteristics of reference way points by behaving like moving average filter.

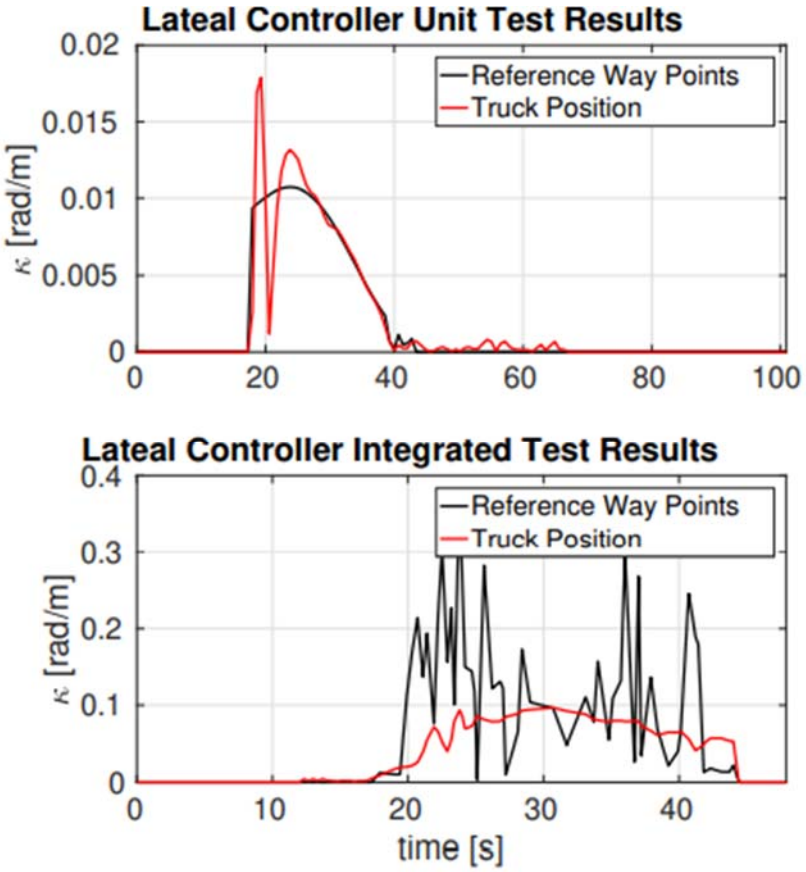

Figure 82: Comparing curvature of reference way point and truck position for unit testing and integrated testing of lateral controllers

4.3. OBU integration

In the GR-TR CBC two partners develop their own OBUs. Each of these OBUs is employed in a different User Stories as can be seen in Table 5. in the following sub-sections a description for all features of these OBUs is presented.

4.3.1. IMEC OBU

4.3.1.1. OBU System Architecture

The OBU architecture is split into two separate OBU units. The first OBU unit will be provided by FORD OTOSAN. This OBU will control the vehicle and process the sensor information. The second OBU unit is installed on the roof of the vehicle and is only connected to the vehicle OBU with an Ethernet connection, power connection and camera connection (depending on the camera setup used in the vehicle). The OBU will contain all the V2X communication hardware and the processing units of sensors that are mounted on top of the vehicle. The two OBU units and their components are shown in Figure 83 below.

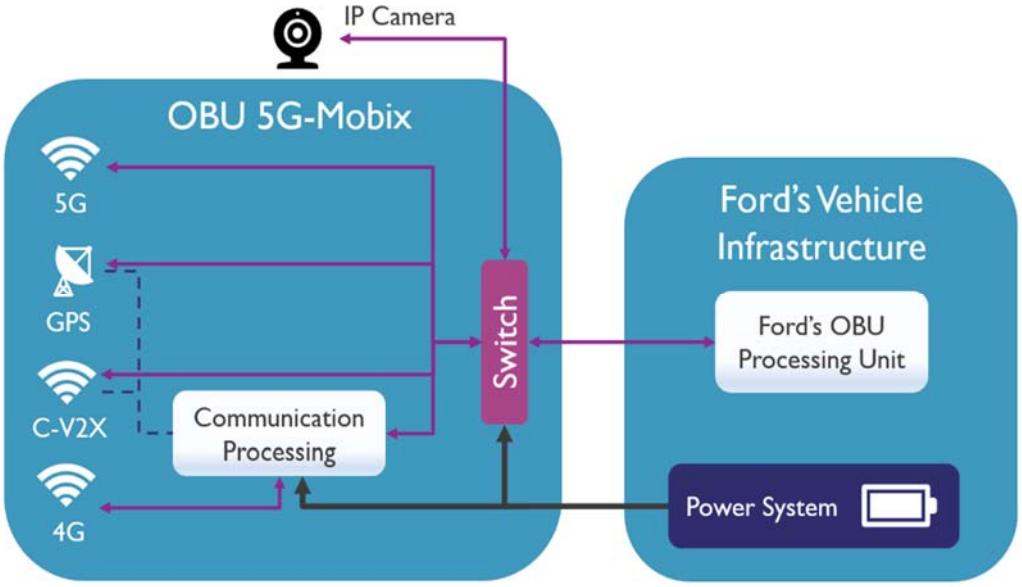

Figure 83: OBU Overview

4.3.1.2. *OBU Software Architecture*

The software architecture of the OBU is based on event streaming architecture. This architecture is chosen to split the software into modular software components that can be run on different processing platforms to reduce the load on the main processing unit. This allows creating sensor connection platforms that can interact with an individual sensor and output a standardised message that can be used in the entire system. This design ensures strong interfaces between the sensors and high-level software components. When a sensor or a V2X component is changed new software components can be implemented to connect the new sensors and new V2X components to these interfaces. This enables the development of high level applications while allowing flexibility in the low-level components.

IMEC's Distributed Uniform Streaming (DUST)-framework will be used to send messages between the different software components. DUST is built on top of traditional messaging protocols like MQTT[8] and ZeroMQ[9]. The goal of DUST is to provide an interface between the messaging protocols and the applications. The developers can switch to a different messaging protocol without changing the application. This can be required because every messaging protocol has its advantages and disadvantages. The messages in DUST are defined with Google protocol buffers. These data structures are used to create the interfaces between the software components that are used in the OBU. These data structures can be extended without losing backwards compatibility between the software components which allows the OBU to be extended as needed without the need of upgrading every software component in the system. This

[8] https://mqtt.org/
[9] https://zeromq.org/

feature will enable the integration of the FORD OBU by only writing a bridge between the required data structures and the OBU software.

4.3.1.3. OBU Hardware Architecture

The OBU contains all communication hardware, V2X processing hardware and sensor processing hardware. Figure 84 below shows the roof unit prototype with all the hardware installed. The centre of the roof unit is the Intel NUC processing unit which will implement the V2X stack and communicate with the OBU within the vehicle. The OBU can access the functionally of the roof unit with the interfaces of IMEC's DUST framework as discussed in the software architecture.

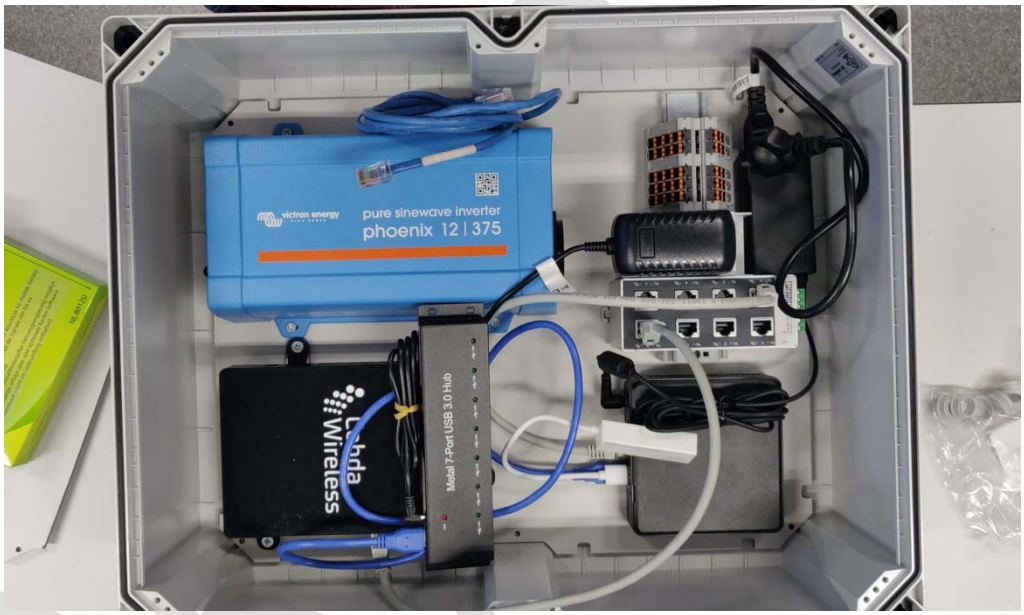

Figure 84: Inside the OBU

Figure 85 below shows the main OBU unit from the outside. The heart of the unit is the Intel NUC processing unit which will implement the V2X stack and communicate with the OBU within the vehicle.

Figure 85: OBU Ports

The OBU unit is supposed to be installed inside the vehicle. All Antennas of the 5G module and CV2X have standard SMA connections and can be installed outside the vehicle. All antennas have magnetic mounts making it easy to use them in any vehicle. The 4G modem is powered by PoE and is should also be installed outside the vehicle. The OBU unit requires 12V DC input and an Ethernet connection to the vehicle unit to operate correctly. The following Figure 86 contains a list of all the hardware of the unit and their specifications.

Figure 86: Front View of the OBU

The OBU unit contains the following list of components:

- V2X processing unit: NUC7iDNKE
- Phoenix gigabit switch 8x 1Gbit/s ports
- C-V2X: Cohda MK6C
- 4G module: Mikrotik wAP LTE kit
- GPS module: Navilock NL-8012U GPS
- 5G modem: Quectel RM500Q
- PHOENIX 12/375 VE.Direct – Schuko
- 2X DIN power plug SN312

4.3.2. WINGS OBU

The WINGS On-Board Unit (OBU) is designed to collect and send real time vehicle information. As a computation platform, the raspberry pi 3 is used with a Quectel RM500Q chipset attached providing 5G connectivity as well as a SIM7600 modem, providing 2G (GPRS)/3G/4G connectivity. The OBU may also work over Wi-Fi connectivity that is build-in the raspberry pi. Power supply is provided from the connected vehicle's battery, through the On-Board Diagnostics (OBD) port connection. There is capability for secondary power supply from AC voltage (220 V). Once powered up, the OBU starts transmitting data with a refresh rate starting from 1 second. More time critical data, such as the proximity sensor readings used for autonomously stopping the truck may be transmitted with higher frequencies of 10-20 Hz. During the verification tests (see deliverable D3.6 (4)), the performance of the Raspberry Pi was validated, and the

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messages transmitted/received from the OBU, met the respective User story latency and throughput requirements.

There is a multitude of onboard sensors with wired connections to the OBU, that provide CO_2, GPS, proximity, acceleration and ECU data. A mini buzzer is used as an alarm indication to inform the vehicle's driver that an obstacle has been detected. The NFC scanner attached, is used for cargo monitoring. The exact specifications of the onboard sensors are provided below. Figure 87 below depicts the design of the WINGS OBU and its external connectivity to sensors, while Figure 88 shows a picture of the actual implemented WINGS OBU and its connected sensors.

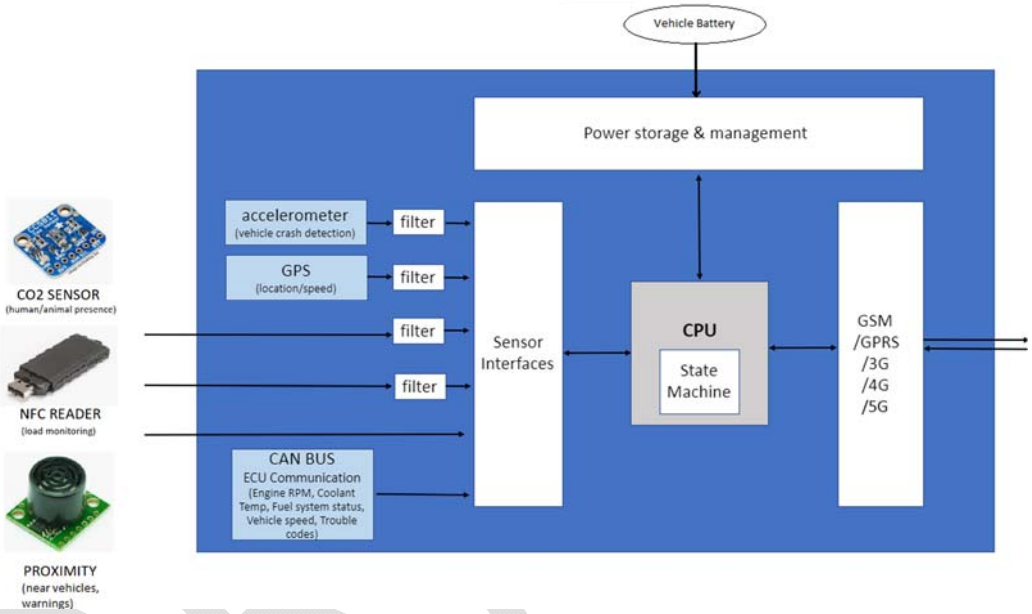

Figure 87: WINGS OBU Diagram

Figure 88: WINGS OBU (with integrated 5G chipset) & connected on-board sensors

4.4. TS contributions to GR-TR vehicles / OBU

FI TS contributes to GR-TR CBC with the remote installation of LEVIS video streaming binaries. The binaries were successfully installed in both See-What-I-See application server and client devices. The devices were further integrated with the IMEC OBUs having positioned in the Ford trucks. The outcome of this contribution is the provision and demonstration of the core functionality of the See-What-I-See video streaming service. This contribution is integrated with the GR-TR CBC management module which has been developed for the registration of new trucks when they ask for access to the current platoon formation and also these ones that are choosing to leave it.

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4.5. Early testing results

In this section several test results are presented. These were done to ensure the good operation of some systems.

4.5.1. WINGS OBU testing

The first version of the WINGS OBU that has been developed was tested over a 5G-NSA testbed provided by Ericsson GR, which is available at COSMOTE premises in Athens. This 5G testbed (which was developed as part of the ICT-17-2018 project 5G-EVE) is identical to the one that is deployed at the GR-TR borders, allowing for accurate testing before taking the implementations to the borders.

The WINGS OBU was brought to the COSMOTE facilities where the 5G testbed resides, in order to test its connectivity and attachment to the 5G network, to troubleshoot any potential issues and to provide a first sense of the performance that can be expected by the 5G Ericsson network in terms of throughput and latency. The achieved performance was also tested over the locally available WiFi connection in order to compare the performance with the 5G network.

The following figure depicts the WINGS OBU and the Quectel testing board at the COMOSTE facilities where the Ericsson 5G testbed resides, during testing.

More specifically the following early tests took place during the test session at the COSMOTE facilities which took place on the 30th of October 2020:

- OBU connection to the 5G network and confirmation of attachment to the 5G-NSA network (success)
- Confirmation of communication (data exchange) between the WINGS OBU and the WINGS remote server, over the 5G network (success)
- Early performance measurements over the 5G testbed targeting the following KPIs: Throughput, E2E latency (success)
- Performance comparison between the 5G testbed and WiFi, based on the WINGS OBU transmitted data (success)

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Figure 89: WINGS OBU & testing board under test in COMOSTE premises, Athens

4.5.1.1. *Early test performance*

After the successful attachment to the Ericsson 5G-NSA testbed a couple of throughput tests were performed in order to observe the achieved throughput. When the 5G SIM card was inserted in a commercial 5G phone available for testing a DL Throughput of 1.2 Gbps was achieved over the 5G testbed. When the 5G SIM card was inserted in the WINGS OBU a max DL throughput of370 Mbps was observed. This is due to the HW restrictions introduced by the Raspberry Pi and its interfaces, which is used as the main CPU of the WINGS OBU. The Raspberry Pi has a HW maximum cap of 400 Mbps on its interfaces, hence the restriction in DL speed originated from the Raspberry Pi, and not the 5G network. Still, this is considered a very successful test, as the achieved throughput of 370 Mbps is more than enough for the purpose of the WINGS "Assisted "zero-touch" Truck Border-Crossing" Use case, and much more than the WiFi achieved throughput which was below 100 Mbps.

The following figure depicts the actual throughput logged by the WINGS OBU during testing.

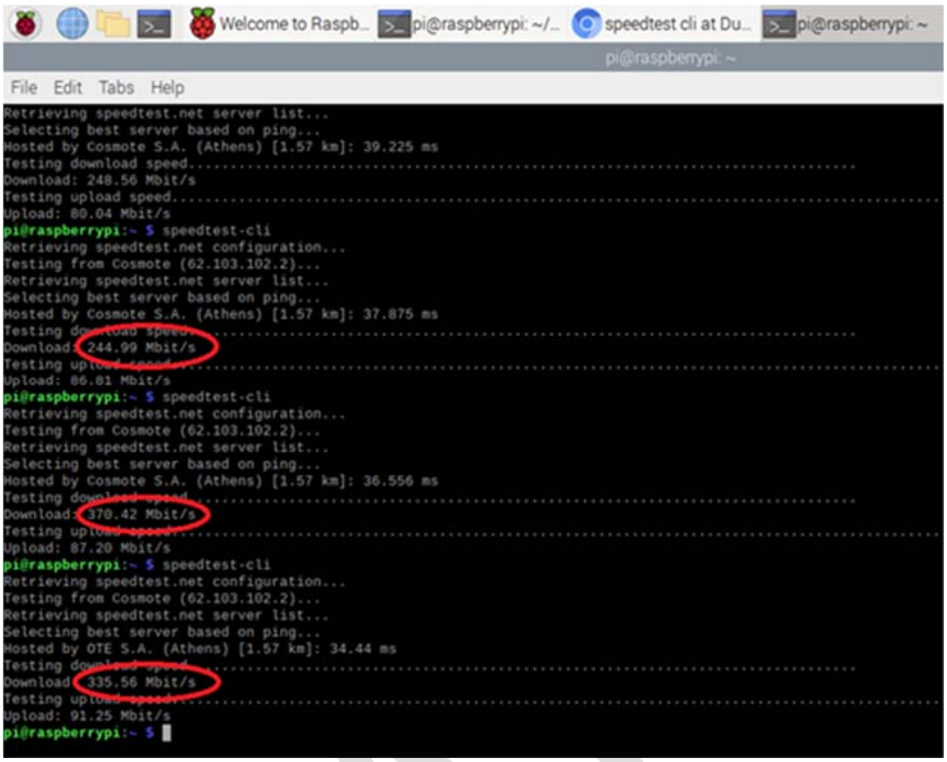

Figure 90: Throughput test via the WINGS OBU

Regarding latency, three different measurement sessions were performed, with transmissions from the WINGS OBU, of the actual data that will be transmitted for the execution of the Assisted Truck Border-Crossing use case. The first two sessions were performed over the 5G network while the 3rdsession was performed over the WiFi network. The detailed measurements for all three sessions are presented in Figure 91 while the average experienced E2E latency per session were:

- Average E2E latency – 1st 5G session = **63.79 ms**
- Average E2E latency – 2nd 5G session = **60.52 ms**
- Average E2E latency – WiFi session = **155.9 ms**

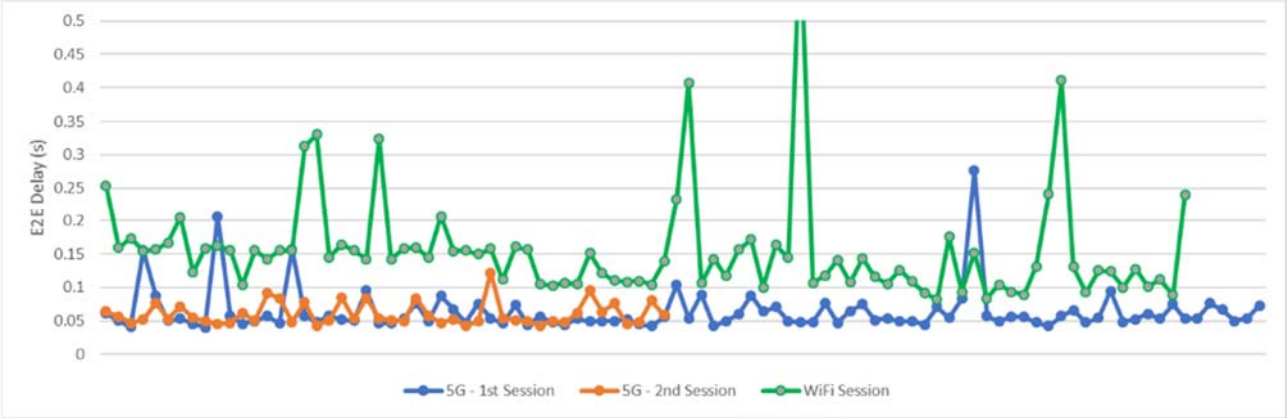

Figure 91: Measured E2E latency of the WINGS OBU transmissions

The reported latency contains the server processing time as well as the round-trip time a transmission from the OBU to the WINGS server and the reception of the relevant ACK and instructions from the server. It is clear that the performance is significantly improved when using the 5G connectivity compared to the WIFi.

The early test session proved very useful, as initially the WINGS OBU could not attach to the Ericsson 5G network. It required intense troubleshooting and a 5G chipset firmware update in order to fix the issues (with support from Quectel). After the necessary updates the WINGS OBU successfully attached to the Ericsson 5G network and performed as reported above. As the 5G network that Ericsson has deployed at the GR-TR follows the exact same specifications and configuration as the 5G testbed located at COSMOTE facilities in Athens (where the test session took place), it is expected that a similar performance of the WINGS OBU will be observed at the GR-TR borders. A more complete testing session will be performed at the Athens based 5G testbed, in order to obtain more useful data and to fine tune the configuration of the WINGS OBU to achieve maximum performance.

4.5.1.2. Final integration test

On December 2021, the WINGS OBU was shipped to the Ford Eskisehir test track, where it was integrated into the Ford truck and the end-to-end functionality of the WINGS led User Story was tested at the Eskisehir track, making use of the 5G network deployed there by Turkcell. The connectivity of the WINGS server with the OBU inside the FORD truck was verified both with a Turkcell SIM card installed and a Cosmote SIM card installed. The CAM and DENM were properly exchanged while the truck was autonomously stopped via a command of the WINGS OBU (testing the VRU scenario). The experienced throughput and latency was nominal (within expected limits) and allowed for the successful exchange of all messages in time and without packet loss. The verification of the proper functionality and the validation of the expected performance were verified via the test logs (from the truck, the OBU and the server).

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4.5.2. IMEC OBU Testing

After completing the assembly of the two OBUs that will be integrated to the FORD trucks, IMEC performed a series of tests in its premises to ensure their expected correct operation. In that direction and as a first step, IMEC firstly tested each component of each OBU individually.

IMEC firstly ensured that each individual component can be accessed remotely and is correctly interconnected through the switch (Phoenix gigabit switch). At the processing unit side (NUC7iDNKE), IMEC installed the Ubuntu 18.04 operating system and all the required software that will be used to further build the necessary functionality for each use case within the GR-TR test site. Then, the GPS module (Navilock NL-8012U) that will be used for time synchronization with the other ITS stations (e.g., OBUs and RSUs) was tested. Concerning the 4G (Mikrotik wAP LTE kit) and 5G (Quectel RM500Q) modems, the wireless interfaces were configured and it was verified that the modems can be connected to the network. Due to the lack of a 5G network in Belgium during the testing period, the 5G modems were tested only on a 4G network. The 5G connectivity will be tested in FORD's and Turkcell's premisses, when the OBUs arrive in Turkey. Additionally, the 5G modems were updated to the latest firmware version provided by Quectel. Regarding the C-V2X PC5 modules (Cohda MK6c), they were updated to the latest firmware version provided by Cohda and configured to communicate with the processing units of the OBUs. Moreover, it was verified that the integrated GPS of each C-V2X PC5 module works as expected and that it can get a GPS fix. Finally, IMEC tested the correct operation of the short-range wireless communication link over PC5.

Afterwards, the operation of the OBUs as a whole and the end-to-end communication between the two OBUs was tested and verified (Figure 92). To this end, IMEC used custom testing tools installed in each processing unit to transmit standardized V2X messages between the two OBUs wirelessly via both short-range C-V2X PC5 and long-range C-V2X Uu links. Once again, at this stage for the long-range

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communication only the 4G link has been tested since a 5G network was not available in Belgium yet. An end-to-end test over 5G will take place in Turkey when the OBUs arrive and become remotely accessible.

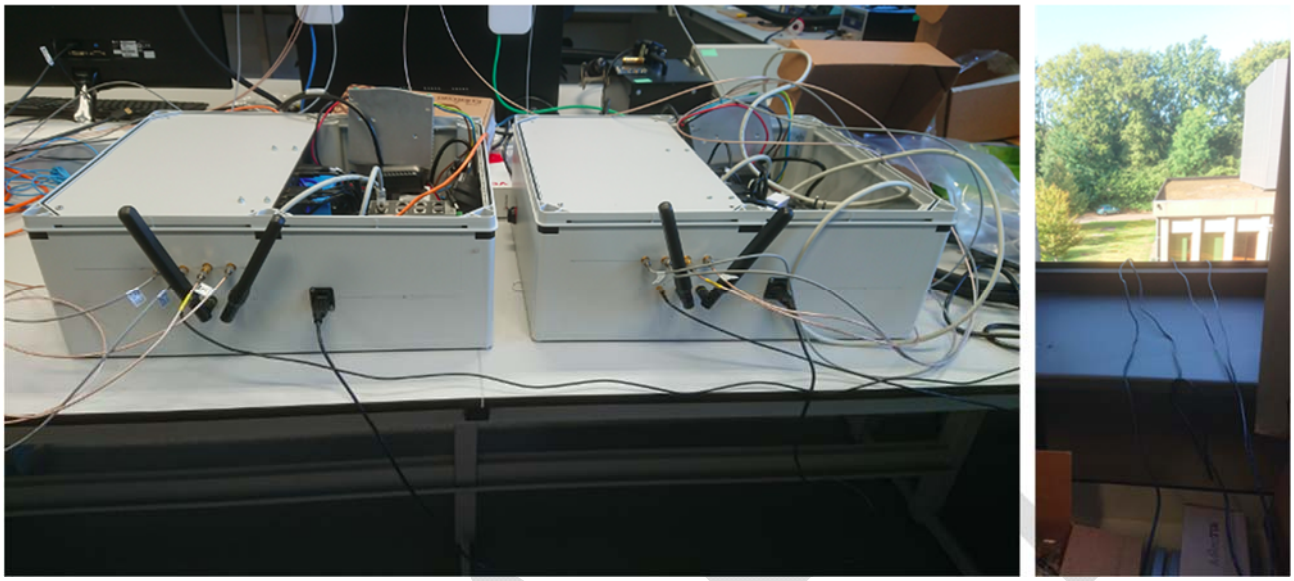

Figure 92: Shows the two IMEC OBUs being evaluated and the cables of the GPS devices that are located outdoors

4.5.3. Truk routing in customs site

Early phase tests of the "path following" algorithm that will be used in truck routing in customs site application was completed. To accomplish this test, path input that normally will come from Tübitak cloud is fed by our MATLAB Simulink model and observed whether controller path follow performance. Fed path contains 500 elements each containing required x,y coordinates and speed information. Path information will change dynamically in the future according to cloud directives.

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Planned path is shown in Figure 93 on the right side as red marked on Ipsala Border Gate map and actual followed path is shown at the same figure on the left side. Tests were conducted with various speed range between 5 to 25km/h and at the all test cases, path is followed successfully.

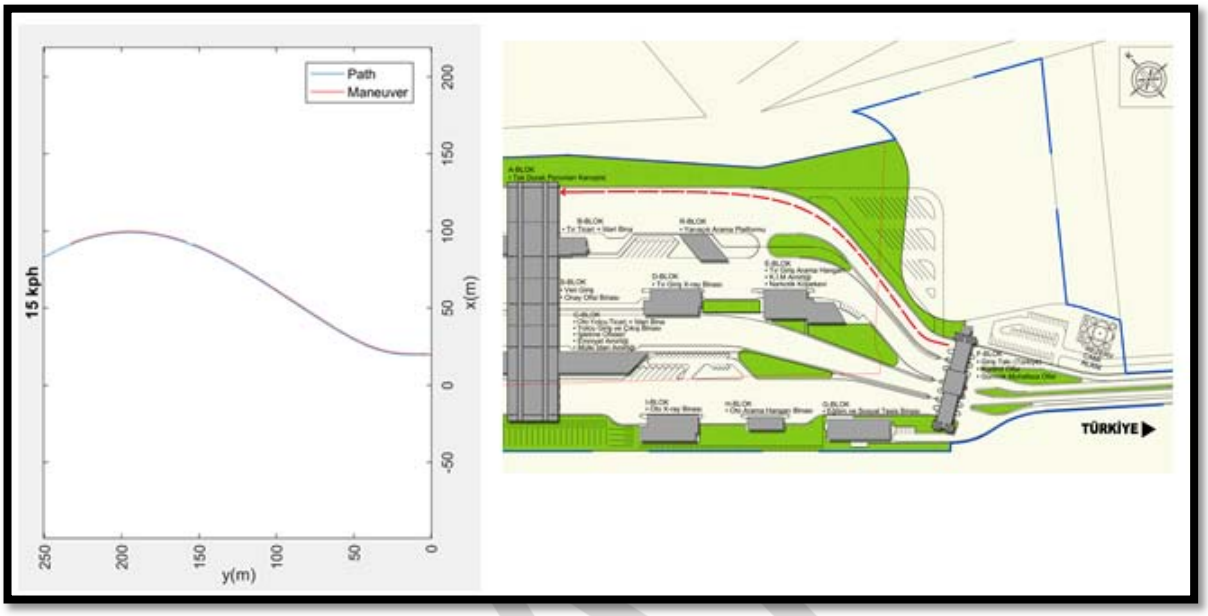

Figure 93: Truck Routing Path Following Test Results

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5. TS VEHICLE INTEGRATION

5.1. DE Setup

5.1.1. Sensors & devices integration

5.1.1.1. VICOMTECH's vehicle

VICOMTECH is using one prototype of automated vehicle for 5G-MOBIX called CARLOTA, equipped with the following sensors and devices:

Table 7: DE TS VICOM's vehicle sensors & devices

Type of Sensor	Units	Characteristics	Purpose
DGPS	1	OxTS Xnav550	Vehicle discovery
4x cameras	4	Valeo Fisheye	Surround View generation
2x 5G Modem	2	Quectel RM500QAEAA-M20-SGASA	Communications
5G Antenna	1	2J Antenna conceptor	Communications
On board computer	1	Vecow RCX-1540R-PEG-9700E64, Nvidia 2080Ti	Video encoding/streaming and SW generation
GPS	2	Ublox EVK8	Clock synchronization
		Navilock 20-61994	Clock synchronization

CARLOTA is a prototype of automated vehicle built from a Toyota Prius platform. CARLOTA prototype ships the following sub-systems necessary to L4 functionalities of automated driving:

- *The sensing system.* This system uses onboard sensors for perception.
- *Computer Vision-driven perception*. This system integrates collaborative perception, forwards obstacle detection, driver attention and fatigue behaviour monitor, road signs interpretation and lateral and lane detection systems.
- *Vehicle platform*. This system is based on vehicle platform CAN to control the actuators of the vehicle.
- *HMI.* The user can visualize all the perception events identified by the system. The HMI is also able to display the system status to the user for maintenance. Specifically, CARLOTA ships two different HMIs specialized in inside as can be checked in
- Figure 95 (information displayed over real-time raw sensors) and outside perception (information displayed over navigation maps):

Figure 94: VICOM test vehicle

Figure 95: Car inside view & Navigation view

Figure 96: CARLOTA's external antenna

CARLOTA already ships GPS sensors, processing units, communication interfaces and OBU. Furthermore, in order to ensure a consistent ecosystem with VALEO's vehicles to focus on communication perspectives of Extended Sensors, the main adaptations on setup pivot around these items:

- Embody VALEO's cameras.

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- Perform Calibration and record geometry setup to facilitate the appropriate and coherent integration of external data flows in the sensor-equipped environment from onboard systems.
- Expand network interfaces with 5G-ready modems compatible with target bands.
- Aggregate IoT-based edge-empowered discovery capabilities to get accurate and wider awareness of surrounding sensor flows exploiting.
- Integrate standard WebRTC stack to RTMaps libraries to allow industry-level workflow.
- Installation of 5G/Sub6 LTE MIMO +GNSS antenna
- Installation of 2x Quectel RM500QAEAA-M20-SGASA modems with PCIECARDEVB-KIT

DGPS, Ublox GPS and the onboard computer were already installed in CARLOTA. This equipment is part of the vehicle and have been used before in another projects. 5G modems and the external antenna were selected to be compliant with the frequency band used in the Berlin commercial 5G networks and in ES-PT CBC. For the GPSs used for clock synchronization, the only requirement was to have PPS signal as output. Most of the commercial GPSs fulfil this requirement, so the GPS were essentially chosen based on the stock availability of the supplier. The cameras were chosen to be the same ones used by VALEO. In order to appropriately install the cameras a deep calibration setup was developed out following the instructions, guidelines and methodology created by VALEO.

The following pictures Figure 97 depict the necessary setup and the markers employed to fully characterise the geometry and alignment of the cameras.

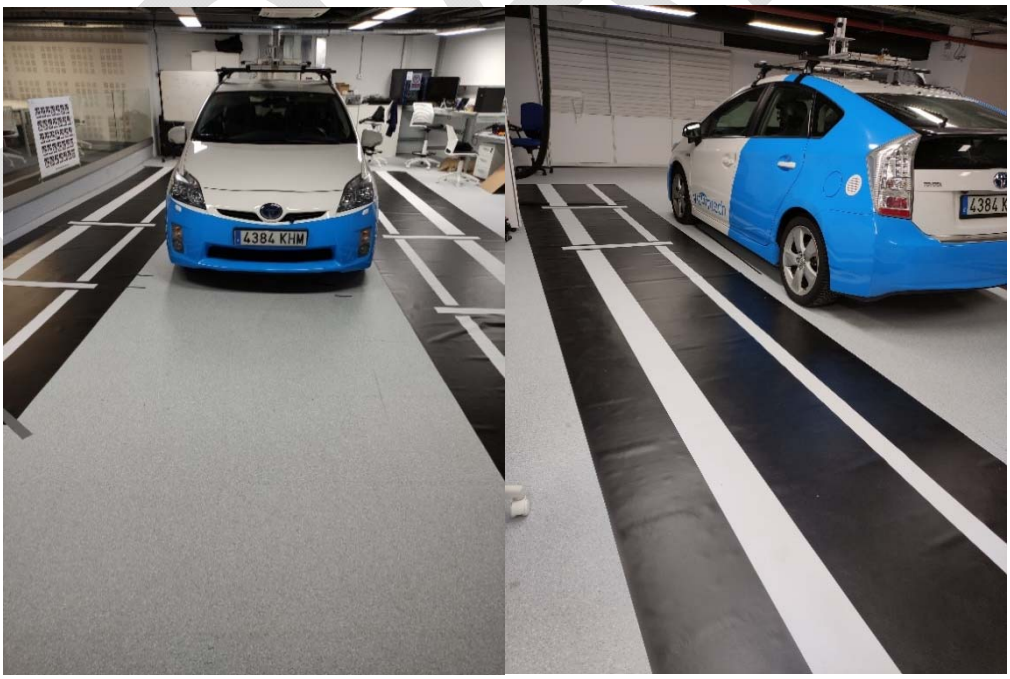

Figure 97: Calibration setup for the cameras

The surround view system consists of four fisheye cameras with large FOV (Field-Of-View): one in the front, one at the rear, and two on each of the side mirrors. We also use an additional fisheye camera in the front (see the left photograph) for reference purposes, not related to surround view generation. The cameras have a resolution of 1280x800 pixels and provide images at a frame rate of 30

5.1.1.2. VALEO's vehicle

VALEO will use a VW Passat Variant (B8) modified for sensor technology and ADAS functionality testing. The vehicle is shown in Figure 98.

Figure 98: VALEO test vehicle, B8

Table 8: DE TS Valeo's vehicle sensors & devices

Type of Sensor	Units	Characteristics	Purpose
Vulcano TCU	1	Version 2.0	Used as 5G modem for PC5 and Uu interface
On-board PC	1	Neousys Nuvo ThinkPad P15 (NVIDIA RTX GPU)	Surround View Application
5G-Modem	1	Quectel RMU500EK	5G Modem for roaming
5G-Modem	1	Netgear M5 5G Mobile WiFi Router (M5200)	5G Modem for roaming
Cohda OBU	1	Cohda Mk6c OBU	Used for C-V2X reception
Cameras	4	Valeo Fisheye	Surround View Generation
GPS	1	iMAR iNAV DGPS Navigation	Location
GPS	1	Navilock NL-8200	Clock synchronization

In autonomous mode the Valeo Cruise4U system (SAE L2-L4) takes over full longitudinal and lateral control (steering wheel, break, accelerator) as well as indicators, gear shift etc. The car will be driven by a professional test driver who can override the system's execution and take over the control at any time. In

manual mode, the driving experience and configuration corresponds to that of a VW Passat production vehicle. Therefore, it is road-legal and insured in Germany.

The surround view system consists of four fisheye cameras with large FOV (Field-Of-View): one in the front, one at the rear, and two on each of the side mirrors. an additional fisheye camera was placed in the front (see the left photograph) for reference purposes, not related to surround view generation. The cameras have a resolution of 1280x800 pixels and provide images at a frame rate of 30

Figure 99: Surround View camera system on Valeo's VW Passat

5.1.1.3. TUB's vehicle

For the platooning US, TUB owns a Volkswagen Tiguan with all the equipment installed to be SAE-L4 capable. At the moment, the software to control the vehicle autonomously is being developed. thus, these capabilities are not considered for the USs where the vehicle used. Another reason not to use the autonomous capabilities is that the DE-TS is located in Berlin city centre, where this kind of tests are not allowed due to security reasons.

Table 9: DE TS TUB's vehicle sensors & devices

Type of Sensor	Units	Characteristics	Purpose
Vulcano TCU	1	Version 2.0	Used as 5G modem for PC5 and Uu interface
On-board PC	1	Nuvo-8208GC Series	Platooning application and EDM proccessing
5G-Modem	1	Quectel RMU500EK	5G Modem for roaming
Cohda OBU	1	Cohda Mk6c OBU	Used for C-V2X reception
Sekonix Cameras	7	SEKONIX SF3324 120° FOV SEKONIX SF3325 60° FOV	Not used in the US
LiDAR	7	Hesai PandarXT 32 Channel Ibeo Scala 1403	Not used in the US

GPS	1	GNSS/IMU – ANavS MSRTK System	Clock synchronization

The main functionalities used from this vehicle are the 5G communications, either via Uu or PC5 interface. Therefore, only the communication devices installed are relevant for the User Stories. The Vulcano 2.0 from Valeo is installed in the back of the vehicle where the 8 antennas needed for the usage of the different 5G frequencies configurations are connected. These antennas are installed and integrated permanently on top of the vehicle.

Figure 100: Integration of the OBU in VW Tiguan from TUB

5.1.2. Automated driving function development

In the Extended Sensors User Story, the Automated driving function enhanced is intrinsically linked to the Computer Vision-driven perception and the HMIs, bringing a see-through-like vision to the surround view.

To launch the Discovery Service and automatically perform a surround view with extended sensors creating a video stream session, we have added a manual HMI component.

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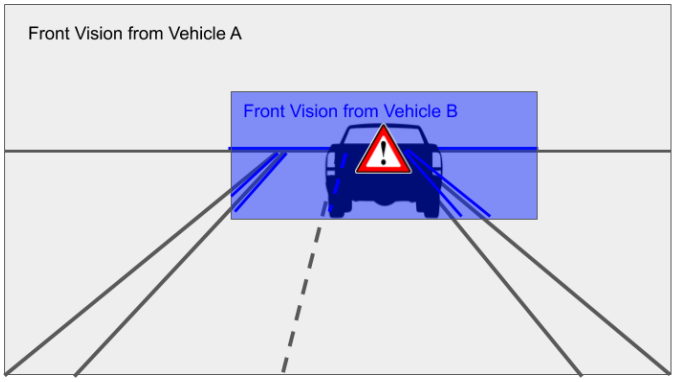

Figure 101: Vehicle's e Field of View

Once this situation is identified, the driver can ask for a surround sensor covering the blocked Field of View (Figure 101).

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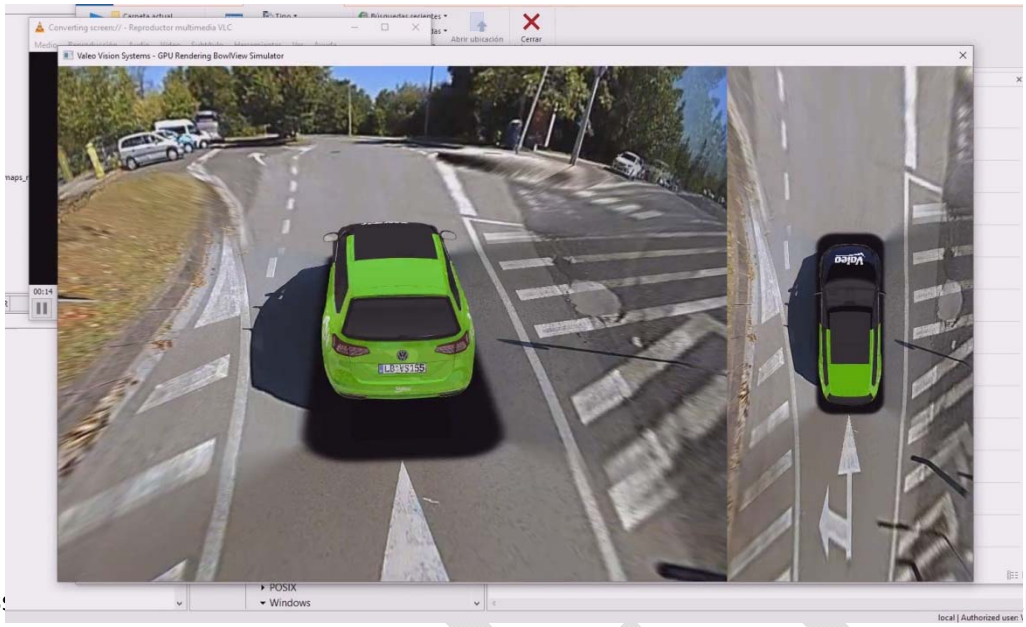
Once the systems establish a session (Figure 102), the surround view with extended sensors is ready and displayed (Figure 103).



In the e-RSU as hange between the two vehicles participating in the platoon and the infrastructure. Thus, the most important metrics in the US are related to latency, so that the vehicles can react on time to events, or follow the platoon leader with very high precision. The platooning control messages are exchanged at a rate of 20 Hz, making the end-to-end latency communication between vehicles crucial. In the testing context of the platooning US, no automated driving function is performed. instead, the communication needed in order to enable automated driving functions is tested and evaluated.

5.1.3. OBU integration

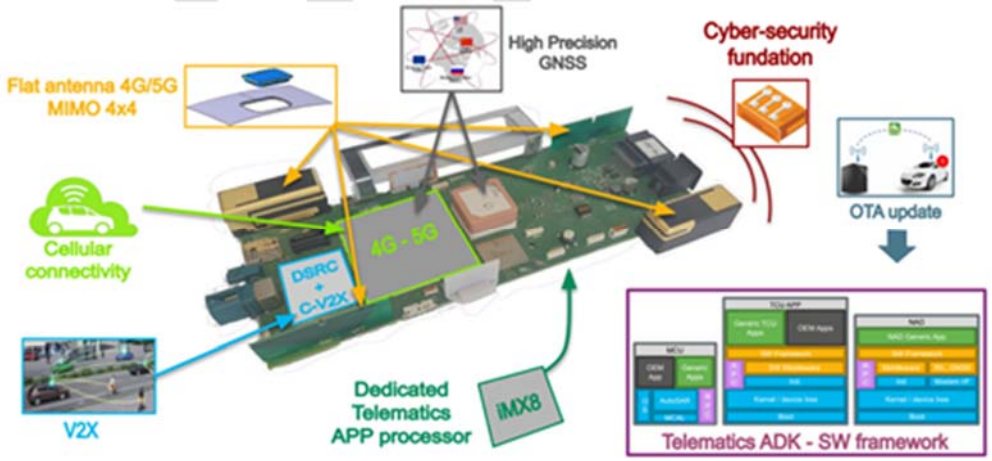


Figure 104: Technologies of Vulcano TCU

The Vulcano 5G modem (Figure 104) is integrated in a Passat Variant (B8) of Valeo and the Tiguan of TUB. The modem is a trunk variant, which means that the modem itself is located in the trunk of the vehicle, and the minimum of four antennas are mounted on the roof of the vehicle. The connection from the host PC to the TCU can be established via Ethernet or via USB. To use the Modem via Ethernet an additional Technica

Media converter is required in between to convert standard Ethernet from the PC to BroadR-Reach of the TCU. If the TCU is connected via USB, it is detected as an external modem, which works with USB sharing of the mobile connection. Functions like DSRC may not be possible with this connection. Vulcano 5G in the EU version can communicate in the following frequencies:

- 2G: GSM900 / DCS1800. 3G: B1, B3, B8
- 4G FDD: B1, B3, B5, B7, B8, B18, B19, B20, B26, B28, B32. 4G TDD: B34, B38, B39, B40, B41, B42
- 5G (Sub-6GHz): n41, n77, n78, n79

The current version 1 of the peiker Vulcano 5G TCU does not support all required network frequencies in SA/NSA mode to demonstrate national roaming in the DE TS UCCs. The envisioned solution is to piggyback an external modem (Figure 105) to the Vulcano TCU to bridge the connectivity gap. The external modem is equipped with the Quectel modem RG500Q in the version "commercial sample 2". The two modems will monitor the signal strengths in their respective band and coordinate the handover if required.

Figure 105: External supplement modem

In Valeo's VW Passat test vehicle, the TCU is mounted along with the data acquisition and processing units in the trunk (black/blue box in below Figure 106). The antenna array is fixed to a rack that is mounted on the vehicles roof.

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Figure 106: Integration of the OBU and antenna system on Valeo's VW Passat

CARLOTA includes two different 5G Modems to the OBU, Quectel RMU500-EK and Quectel RG500Q-EA CS2 which are interfaced and powered though USB cable. The RG500Q-EA CS2 model is fully compatible with the Deutsche Telecom SA band n1 to be used at Berlin with the Quectel RMU500-EK is compatible with commercial NSA n77 and n78. Both would allow a quick national roaming shifting the traffic gateway through one or another modem.

In order to get them working the vendors supplies a driver for Linux and Windows systems. In fact, the drivers for Linux are available from the standard Kernel 5.4.20.

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5.1.4. Early testing results

5.1.4.1. E-RSU-assisted Platooning US early testing results

The platooning US has been fully tested for the demo in the DE-TS realized in September 2021. different scenarios were tested, combining different configurations of communication via PC5 and/or Uu. In the September demo a hybrid network configuration of PC5 and Uu simultaneously was tested. The PC5 interface from C-V2X is used to exchange platooning messages between the platoon vehicles and also to receive Service Announcement messages from the RSUs. This message contains the address of the MQTT broker used to receive infrastructure ITS messages via Uu interface.

In the September demo, no relevant measurements were taken, apart of physical layer metrics regarding the 5G network status. The preparation of the full trials for the different scenarios are almost ready, so that in the actual month of February 2022 the driving tests can be performed.

5.1.4.2. Extended Sensors US early testing results

The end-to-end solution of extended sensors User Story has already been tested in the DE TS in Berlin. Several road tests were carried out using the developed dual modem solution. In the tests, different setup combinations were used. More specifically, the following parameters were modified: MEC infrastructure (MobiledgeX or DAI-Labor's data centre), Mec Handover (yes or no), use of WebRTC Gateway (yes or no), and adaptative video bitrate (yes or no).

O2 and DT commercial 5G NSA networks were used in the tests. In each vehicle there were two Quectel modems with one SIM of each network operator.

The trials are still ongoing, and the results will be described in detail in the WP5 deliverables. As an example, in the following figure, the throughput obtained in a drive using adaptive bitrate is depicted. It can be noted that there is an interruption time of around 3 seconds when the dual modem solution switches from one operator to the other. The measurement was performed using TACS4 performance tool, which is able to perform this kind of measurements even when there is a change of network operator with the corresponding loss of coverage during the process.

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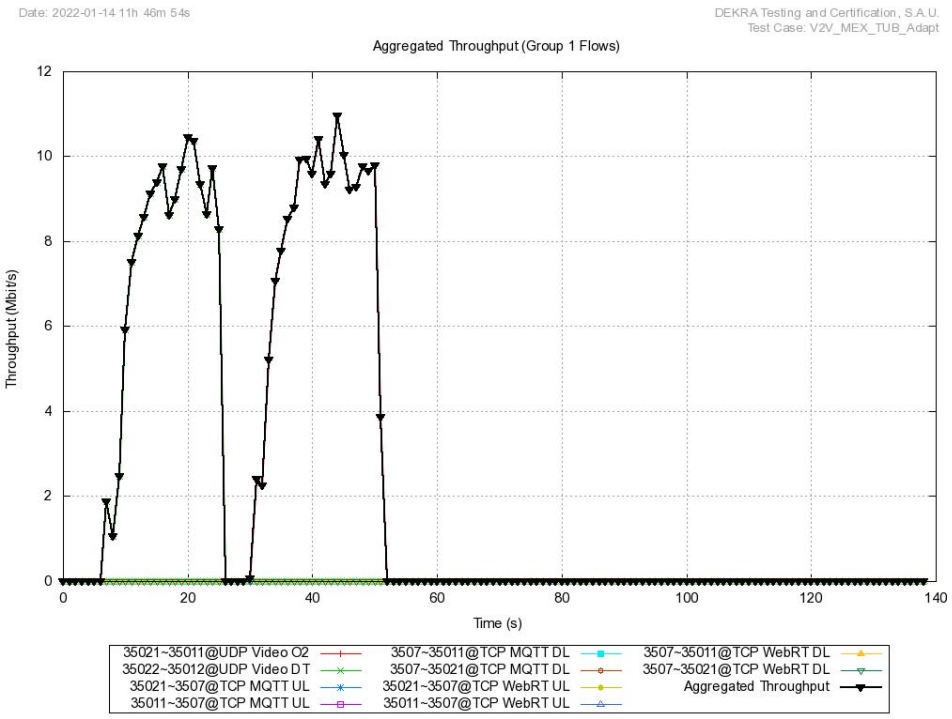

Figure 107: Throughput obtained with Extended Sensors User Story

5.2. FI Setup

5.2.1. Sensors & devices integration

The primary vehicle utilised in the FI TS is an SAE L4 connected and automated vehicle (nicknamed 'Ava') provided by SENSIBLE4 and is equipped with the following sensors listed in Table 10 and described in more detail in D2.4 (2). The Ava sensors utilised in the FI TS remote driving (RedundantNE) User Story are the front and rear LiDAR cameras and (HD) camera, which stream real time visual data to the remote operating centre (ROC) to provide situational awareness for the remote human operator. Moreover, the vehicle is also equipped with other sensors that are utilised by the vehicle in the autonomous driving operations, with the data remaining in the vehicle side and not transferred to the ROC (unlike the LiDAR and video streams).

Table 10: FI vehicle equipment

Type of Sensor	Units	Characteristics	Additional info
LiDAR	2	3D LiDAR	Velodyne VLP-16 360° perception 3D LiDAR
Camera	2	Colour camera	Front and back cameras
RADAR	3	GPR	Bosch GPR 1.0
GNSS	1	GNSSS RTK	
Inertial	2	IMU	

Odometer	4	Wheel odometer	
Steering sensor	2	Steering angle sensor	
PC	1	PC	Navigation PC for data processing
Communication	1	OBU	Multi-SIM OBU operating in NSA and SA modes

The vehicle at SENSIBLE4 is road legal and has been used for demonstrations and testing on open roads in Finland. The vehicle counts with a navigation PC on-board which is configured to use the 5G multi-SIM OBU for network connection. SENSIBLE4 vehicle is showed in Figure 108.

Figure 108: SENSIBLE4 connected and automated vehicle for remote driving User Story

In addition to the SENSIBLE4 vehicle, the FI-TS also utilises a connected vehicle provided by AALTO for conducting trials for the extended sensors (EdgeProcessing) User Story. This AALTO vehicle is a Ford Focus model vehicle configured generally as an Advanced Driver Assistance Systems (ADAS) research platform and equipped with various sensors. However, the main sensors used for the EdgeProcessing User Story include a GPS antenna for localisation purposes and a forward view HD camera that streams video to a designated MEC to be processed by the HD Maps application. This connectivity is provided by the 5G multi-SIM OBU deployed in the vehicle.

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Figure 109: AALTO connected vehicle for extended sensors User Story

5.2.2. OBU integration

The FI-TS evaluated multiple OBU solutions as noted previously in D2.4 (1). The solution that was eventually selected for trials in FI-TS was a multi-SIM solution based on a router product from Goodmill Systems[10] used for critical communications scenarios. In addition to the local trials in FI-TS, the multi-SIM solution will also be contributed for agnostic testing in the ES-PT CBC to provide insights on performance of multi-SIM implementations in realistic cross-border environments and comparisons against conventional roaming implementations. The multi-SIM OBU (see Figure 110) includes two 5G modems and two SIM slots that allow for connectivity to two different PLMNs. The modems utilised are Sierra EM9191 modems with Qualcomm Snapdragon X55 chipsets and support operation in LTE and 5G sub-6GHz bands (including n78 band used in FI-TS). The initial versions of the modems that shipped with the router in M26 only operated in NSA mode, but a firmware update was provided by the vendor later in M32 to also support SA mode operation.

[10] https://goodmillsystems.com/

Figure 110: FI-TS 5G multi-SIM OBU which includes the router (left) and 5G modems (right)

The scalability of the multi-SIM OBU in terms of number of PLMN connections (SIMs and modems) supported is limited by the form factor of the modems used. Originally the OBU was designed to accommodate four SIM cards but only two SIM slots are used due to the M.2 3052 form factor of the Sierra modems (see Figure 111).

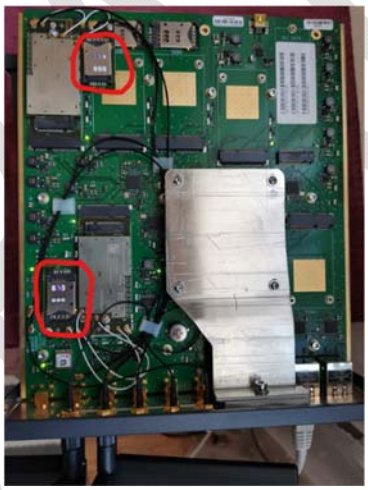

Figure 111: Internal board view of the FI-TS multi-SIM OBU with the two SIM slots used marked in red circles

The multi-PLMN operation of the FI-TS OBU is enabled by the use of Mobile-IP (MIP) tunnelling approach. As noted previously, the OBU is based on a commercial product that is already used in practical applications for critical communications over IP by verticals in public protection and disaster recovery. The end users in this case have very stringent requirements on service continuity, security, and reliability, which are also very relevant for CCAM use cases. The MIP implementation for the OBU addresses those requirements through encrypted tunnels, fast tunnel switch-over, session persistence, selecting always the best (or prioritised) link or alternatively aggregating traffic over multiple links. Additionally, the approach provides flexibility for ensuring service continuity of both 3GPP access (5G NSA/SA, public LTE, private LTE etc.) and non-3GPP

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access (Wi-Fi, satellite etc). The access flexibility of this approach is basic precursor to the Access Traffic Steering, Switching and Splitting (ATSSS) feature enabled by multipath TCP (MPTCP)[11] in 3GPP Release 16.

Figure 112 provides a high-level illustration on multi-PLMN operation with the FI-TS multi-SIM OBU in an environment with overlapping coverage from two 5G PLMNs. The MIP GW server terminates MIP and VPN tunnels coming from OBU, with MIP providing session persistency while VPN encrypts traffic. The Goodmill Manager provides an admin interface for configuring and monitoring the OBU. In link selection mode, the OBU continuously monitors different PLMN connections and selects the best one based on pre-configured criteria that includes signal strength, latency and radio access technology (RAT) priority. Whereas, link aggregation mode allows for splitting and simultaneous routing of traffic over the two PLMNs.

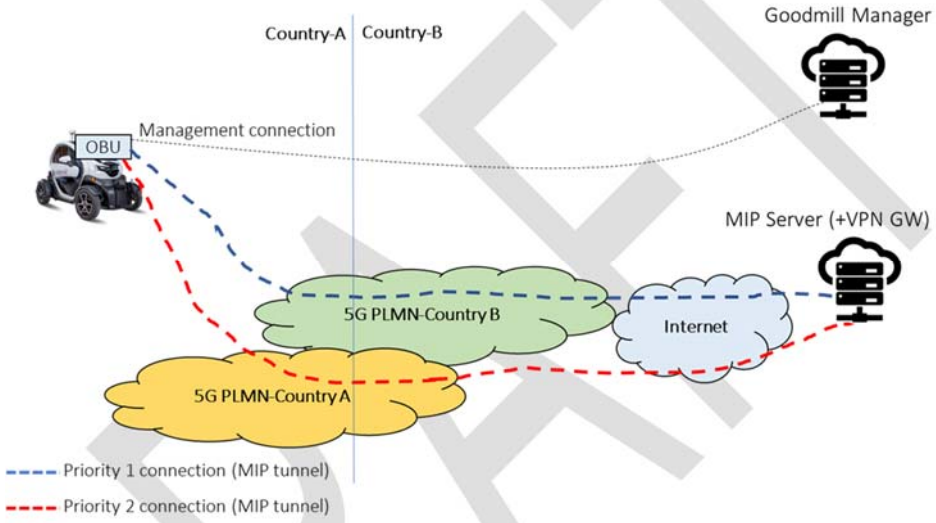

Figure 112: Multi-PLMN connectivity using the FI-TS multi-SIM OBU

The actual deployment and integration of the multi-SIM OBU to the FI-TS vehicles considered access to power supply and cabling to on-board PC and other devices deployed in the vehicle. In the SENSIBLE4 vehicle described previously the OBU was placed in the rear, while the antennas are placed on the roof of the vehicle for enhanced coverage by avoiding penetration losses into the vehicle (see Figure 113).

[11] 3GPP TS 23.316 Wireless and wireline convergence access support for the 5G System

Figure 113: Deployment and integration of the multi-SIM OBU to the SENSIBLE4 vehicle

5.2.3. Early testing results

The multi-SIM OBUs in FI-TS have gone through a series of iterative configuration and testing operations to ensure their reliable operation in the series of local trials in FI-TS and later testing activities planned for the ES-PT CBC. This includes initial configuration, testing and verification of multi-PLMN operation, and the later repeated activities with subsequent upgrades for the OBU. These activities have been carried out both in routine tests, as well as in more intensive agnostic and specific measurement campaigns as part of the local trials as summarised in Table 11.

Table 11: Summary of configuration and testing activities for the FI-TS multi-SIM OBU

Local tests and trials	Description of multi-SIM OBU configuration and testing activities for local and CBC trials
Pre-trials M27	• Verification testing Multi-SIM OBU (NSA mode) for remote driving User Story in multi-PLMN environment. • Testing different deployment aspects (e.g. antenna placement).
Early trials (M29/M30)	• Testing of different configurations of 5G NSA network (re)selection criteria to reduce 'ping-pong' effects • Testing implemented logging and measurement framework to obtain KPIs and network switching logs from the multi-SIM OBU
Testing (M32/M33)	• Verification testing for operation in 5G SA mode in indoor SA lab deployment
Trials (M34)	• Comparative test runs for single-SIM versus multi-SIM scenarios within the context of remote driving trials

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	• Maintaining log of on-the-road incidents that impact obtained KPI measurements
Trials (M38)	• Extended sensors trials utilised the multi-SIM OBU in link selection mode, with network (re-)selection also triggering MEC migration
Ongoing tests (M40-)	• Preparatory configurations and measurement tool setup for the agnostic testing activities to be conducted in ES-PT CBC • Comparative agnostic testing for the new link aggregation upgrade versus original link selection feature

The aforementioned tests and early trials with multi-SIM OBU have been conducted multi-PLMN environment of the FI-TS which includes 5G research testbeds (two PLMNs) deployed in the Otaniemi area as well as multiple 5G networks commercial mobile network operators with coverage in the same area for additional trialling activities and benchmarking purposes. One of the results highlighted herein are from the remote driving trials of M34, whereby, the multi-SIM OBU connected to two of those commercial 5G mobile networks. Each of the two networks operates in NSA mode utilising the 3.5 GHz TDD band for 5G NR (each with 130 MHz bandwidth allocation) and LTE anchors in the 2.6 GHz band. The coverage maps for these networks obtained from drive tests carried out prior to the demonstrations is shown in Figure 114 (here labelled Network-A and Network-B). In the link-selection mode, the multi-SIM OBU preferably provides a data connection via the primary network (Network-A) but selects secondary network (Network-B) where Network-A quality falls below a pre-configured threshold.

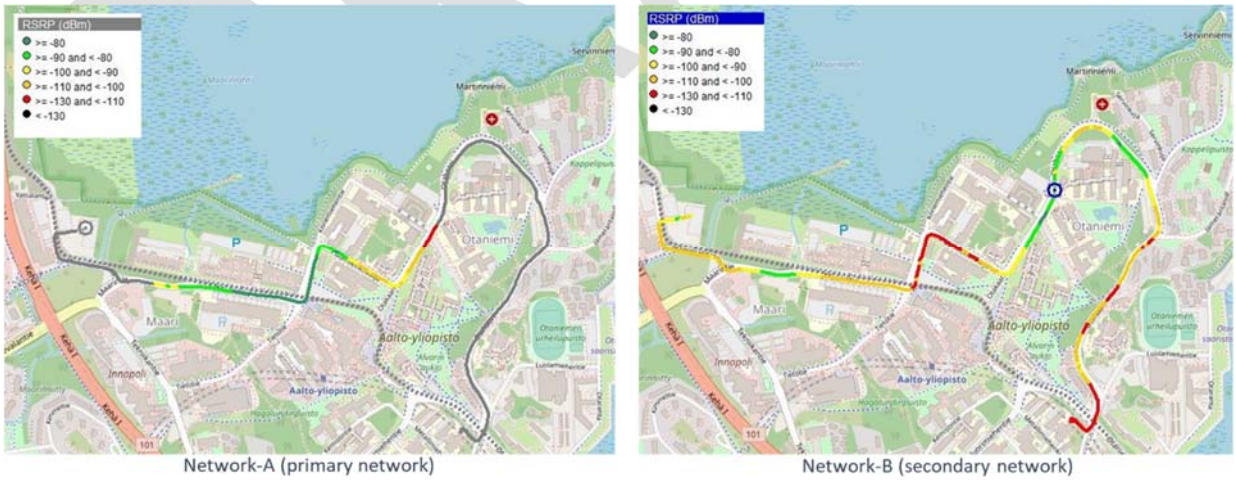

Figure 114: Coverage maps for the networks utilised in the early remote driving trials

The trials utilised the SAE L4 autonomous vehicle from SENSIBLE4 described earlier in Section. In the remote driving scenario, the autonomous vehicle utilises 5G vehicle-to-network (V2N) connection

provided by the multi-SIM OBU to transfer two (front and rear) 3D LIDAR streams (UDP traffic, 10 Hz frame rate, 7.5 Mbps per stream), video feed (UDP, H.264 encoding, 30 frames/s, 8 Mbps) and status messages (TCP, 1 message/s, 0.1 Mbps) from the vehicle to the ROC (in the uplink direction). The video and sensor data provides the human operator a "driver's view" allowing the human operator to send appropriate command messages (TCP, 5 kbps) back to the L4 vehicle (in the downlink direction).

The remote control or driving of a vehicle presents stringent requirements on connection between the vehicle and the ROC. Furthermore, the whole control loop needs to be kept tight. The trial demonstrated how the multi-SIM operation is able to utilise the multi-PLMN environment (Network-A and Network-B) to ensure availability of the V2N and the uplink capacity is guaranteed for the transmission of the data feeds from the vehicle for demanding streams (see Figure 115), and timely reception of command messages from ROC to the vehicle.

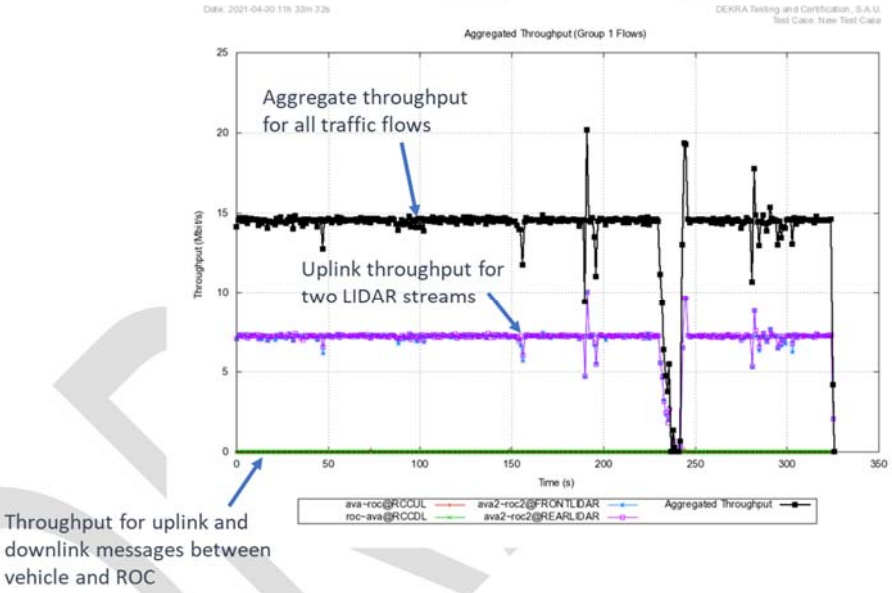

Figure 115: Exemplary throughput measurements for continuous uplink traffic flows using the multi-SIM OBU

At the current time of reporting, the testing and configuration of multi-SIM OBU are ongoing in particular to evaluate the performance of the link aggregation mode upgrade. The target is to ensure full readiness of by OBU in time for the agnostic tests in the ES-PT CBC and final trials and demos in the FI-TS.

5.3. NL Setup

5.3.1. Sensors & devices integration

To carry out the User Stories testing and trialling, the NL TS vehicles are being equipped by the following sensors, as can be seen in Table 12. Three vehicles are developed in NL TS and used in different User Stories:

Table 12: Vehicles used in NL TS for different User Stories and vehicles, Connected Vehicle (CV) and Connected Autonomous Vehicles (CAV)

User Story		TNO	SISSBV	TU/e-AIIM	VTT
	Type of vehicle:	CV	CAV	CAV	CAV
Extended Sensors		x (lead) – *no additional sensors*	x		
Remote Driving			x	X (lead)	
Advanced Driving (CoCA)				x - no additional sensors	x (lead) no additional sensors

The TNO vehicle is a Connected Vehicle (CV) only, so it is equipped with additional communication (and no automated driving functions). Therefore, it will not be described in this section 5.1.3 further.

5.3.1.1. TU/e-AIIM vehicle

TU/e provides and uses one automated vehicle and uses this in 2 User Stories: Remote Driving and Advanced Driving (CoCA User Story, led by VTT). The vehicle is a 2018 Prius PHV (Figure 116), which is equipped with sensors, connectivity and hardware to support CCAM functionalities.

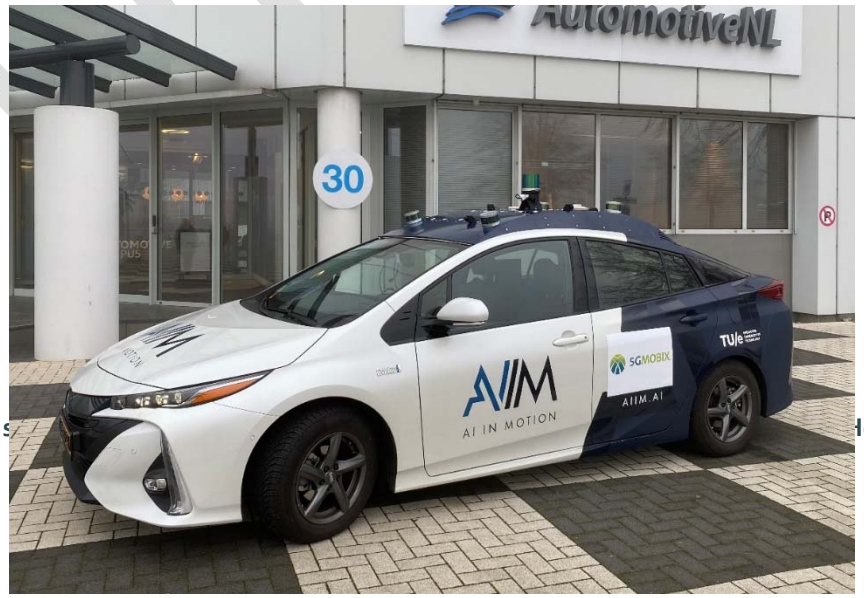

Figure 116: Sensor s… …elmond, The

This vehicle was built based on a previous research vehicle (which was based on a Toyota Prius 2010 model, like the SISSBV vehicle). The sensors are set for 5G-MOBIX. The vehicle will be equipped with the following sensors and hardware depicted in Table 13:

Table 13: Sensors and HW platforms overview of TU/e vehicle for use in Remote Driving and Advanced Driving User Stories

Sensor	Number	Type	Car position	Horizontal field of view	Vertical field of view	Range
3D LIDAR	1	Ouster	Roof	360°	40°	~ 150m
Remote Driving cameras	4	Mono-camera	Roof	120°	-	~40 m (ped.)
RTK-GPS (incl. FOG-IMU)	1	Advanced Navigation	Trunk	-	-	-
Communication unit	1	5G modem (KPN)	Trunk	-	-	-
Ethernet switch	1	10Gbit	Trunk	-	-	-
Computing units	2	nVIDIA DrivePX2 carPC	Trunk	-	-	-

For the 5G-MOBIX Remote Driving User Story, the vehicle has been extended with a 360° camera set-up.

The integration of these sensors was done with the collaboration of the connectivity and vehicle automation teams in order to offer the required interfaces to let all these sensors communicate with the 5G-OBU. As these vehicles have been already used for demonstrations in other projects, all sensors are already in place in the vehicles. Interfaces with the 5G-OBU and the internal PC are also defined in order to provide and harmonize the data format and facilitate integration. This communication interface is now validated and tested.

5.3.1.2. SISSBV vehicle

Siemens provides one connected automated vehicle for the User Stories Remote Driving and Extended sensors. This vehicle is a Toyota Prius (model XW30), shown in Figure 117, which was altered to address the requirements for automated and connected driving. The Prius is used as a research and development platform for automated driving technology within Siemens. While the vehicle is outfitted with numerous equipment, only a subset is used for the 5G-MOBIX User Stories. The following table states the equipment that will be used in the vehicle for 5G-MOBIX:

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Table 14: Sensors and HW platforms overview of the Siemens vehicle for use in Remote Driving and Extended Sensor User Stories

Sensor	Number	Type	Car position	Horizontal field of view	Vertical field of view	Range
Remote Driving cameras	4	Mono-camera	Roof	120°	-	~40 m (ped.)
GPS (incl IMU and RTK)	1	1. Ublox Lane Accurate Navigation 2. NTRIP receiver	Trunk	-	-	-
Communication unit	1	• 5G modem (KPN) • Cohda MK5	Trunk	-	-	-
Hardware						
Ethernet switch	1	Gigabit	Trunk	-	-	-
HMI	1	Touchscreen	Dashboard	-	-	-
Computing units	2	NVIDIA DrivePX2 Custom PC	Trunk	-	-	-
CAN Router	1	CAN bus router	Trunk	-	-	-

All equipment listed is used to enable the connected driving with 5G-OBU. The Custom PC provides the interfaces for logging and facilitates any data stream from other sensors.

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Figure 117: Sensor setup of the Siemens vehicle during January 2020 KPN 5G FieldLab event in Helmond, The Netherlands, demonstrating the Remote Driving User Story

5.3.1.3. VTT vehicle

The Automated Vehicles team has a set of research prototype vehicles. For the 5G-MOBIX trials the Martti vehicle is used. This is a VW Touareg which was modified for automated driving. The vehicle is equipped with a set of environmental perception sensors, such as RADAR and LASER scanners (Table 15). The vehicle architecture is based on DDS (Data Distribution Service), through which the data of the sensors and the information received through 5G is made available to the other vehicle modules, such as trajectory planning and actuator activation.

Table 15: Overview of hardware components of the VTT Martti

Sensor	Number	Type	Car position	Horizontal field of view	Vertical field of view	Range
3D LiDAR	3	• 1 x ibeo Lux • 2 x Sick	• Front	110 °	3,2 °	up to 200 m
RADAR	1	• Conti SRR 208	• Front	150 °	12 °	< 50 m
Camera	1	• Stereo	• Front			
Weather station	1	• Airmar	• Trunk			
Hybrid Communication	1	• Intrinsyc C-V2X hybrid LTE & ITS G5	• Trunk			
Mobile Communication	1	• 4G/5G Communication	• Trunk			
GNSS	1	• ublox RTK-GPS	• Trunk			
Inertia	1	• IMU	• Roof			
Antennas	4	• GNSS Receivers	• Roof			

Additionally, a research connected motorcycle "Jarno", a modified KTM motorcycle, which is equipped with a 5G OBU, will be used for testing the CoCa User Story in Tampere. Figure 118 shows the two VTT vehicles.

Figure 118: VTT research prototype vehicles Martti and motorcycle Jarno

For the tests in the Netherlands and the ES-PT CBC, VTT has developed OBUs, consisting of laptop, 5G modem, GNSS receiver and inverter, which can be easily installed in vehicles from 5G-MOBIX partners or in rented vehicles.

5.3.2. Automated driving function development

In NL Trial site, the 3 CAV are being set up as described in section 5.1.3. The motorcycle "Jarno" is a CV and for this reason is not include in current section.

5.3.2.1. TU/e-AIIM vehicle

The TU/e vehicle is being used in the Remote Driving & Advanced Driving User Stories on NL site User Story. The Remote Driving User Story focuses on the function to stream video data from the vehicle to a remote station. Additionally, this vehicle will also be used, for testing 5G mmWave localisation (Q2-2022). Since this was a new vehicle only parts of the former TU/e test platform (Prius 2010) could be exchanged to this new platform. Some parts were completely redesigned, especially the low-level safety for remote control, and the sensor setup rooftop. This change in rooftop design, provides a more flexible set-up for environmental perception sensor testing and antenna integration. In the architecture this reflected that the function localisation, sensor fusion, obstacle qualification and filtering and world model had to be adapted.

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By adding a 5G NR enabled mmWave localization, the sensor fusion module and world model is being updated now (not yet finished to enable the 5G localisation function). Since the video stream and the localisation function operate on different 5G bands, two separate modules have been integrated to support this. Currently the module for remote driving is integrated while the module for localization is still in development. In Figure 119 is shown the AD function development to support remote driving User Story.

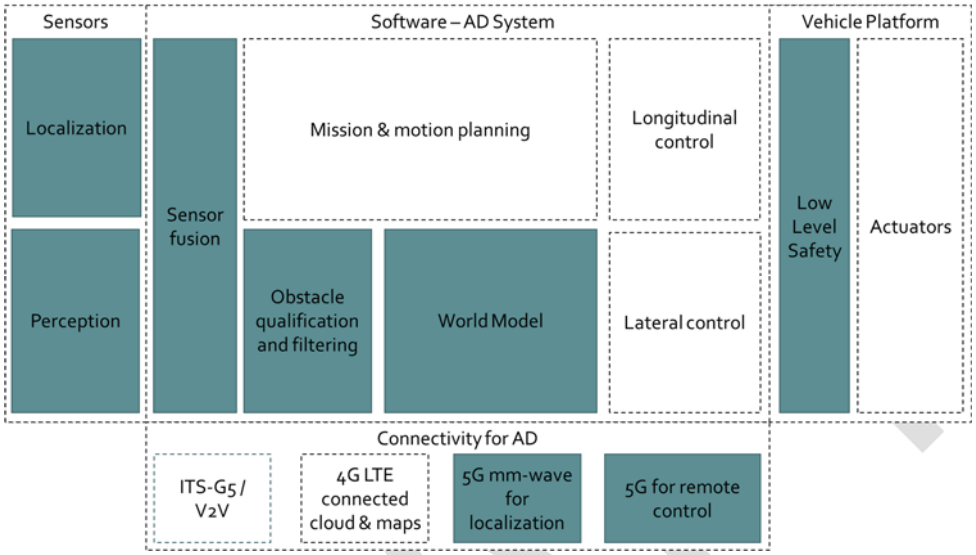

Figure 119: TU/e vehicle AD function development to support Remote Driving User Story

5.3.2.2. SISSBV vehicle

The Siemens vehicle uses a similar set-up as the TU/e-AIIM (sub-section 5.3.2.1) and therefore similar function had to be adapted for the SISSBV vehicle in the remote driving User Story, mainly focusing on Perception, 5G for remote control and low-level safety.

5.3.2.3. VTT vehicle

The VTT research prototype vehicle Martti is used for the Cooperative Collision Avoidance (CoCA) User Story. CoCA uses the Manoeuvre Coordination Service (MCS) for negotiation between the vehicle and infrastructure.

The following adaptations were made to the vehicle software:

- MCS (Maneuver Coordination Service): generation of planned (collision-free) trajectory and desired (intended manoeuvre) trajectory, and interpretation of the message
- Sensor fusion: fusion of the sensor own data and the information coming from MCS from other vehicles
- Obstacle qualification and world model: integration of the information from MCS
- Mission and motion planning: evaluation of the advice and manoeuvre suggestions from other vehicles. Selection between planned and desired trajectory.

An overview of modified modules is shown in Figure 120.

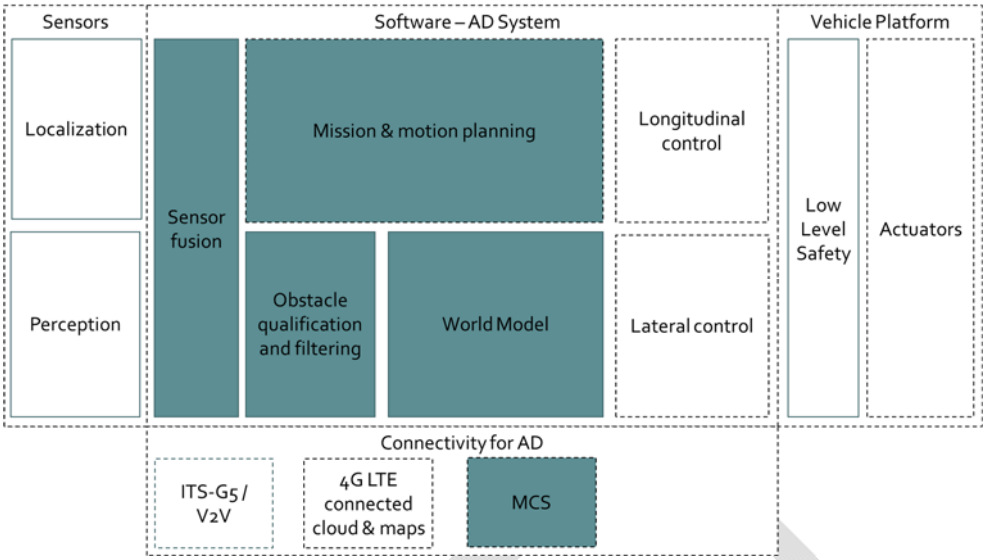

Figure 120: VTT vehicle AD function development to support CoCA User Story

5.3.3. OBU integration

In NL Trial Site, TNO is actively working on developing a 5G based OBU. Other partners use KPN provided 5G modems to integrate into their vehicle compute modules.

5.3.3.1. TNO 5G OBU

TNO has developed an OBU with integrated 5G capabilities. The OBU is a x64 board running Debian OS. This OBU will be placed in TNO's vehicle alongside with a smartphone for HMI functionalities (see Figure 121):

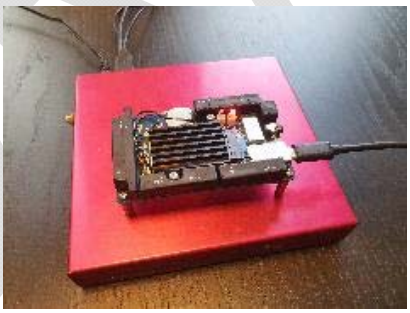

Figure 121: TNO 5G OBU

The OBU's attached 5G modem is based on the SDX55 (LE1.2 Baseline) chipset from Qualcomm. The OBU hosts an ITS software stack which will be used to support the Extended Sensors use case. this stack will be coupled with a smartphone, over Wi-Fi, which will function as an HMI for the driver. The stack supports sending CAM messages as well as generating merging advice for the driver/CAD vehicle based on the combination of incoming CPM and CAM messages. Below figure shows an overview of the OBU stack.

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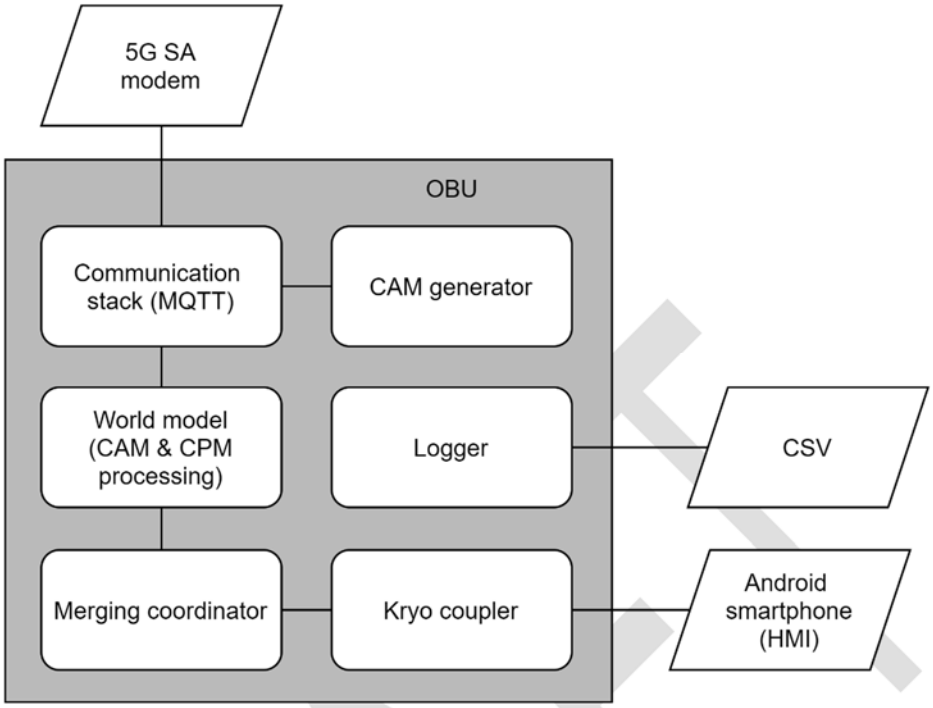

Figure 122: OBU stack

Below figure shows the test setup as was used during the initial (agnostic) tests. An Iperf server is used as an endpoint for the latency and throughput measurements. The Iperf server can be either hosted on the edge (in Helmond) or in the core (in The Hague). All measurements are done on the OBU itself.

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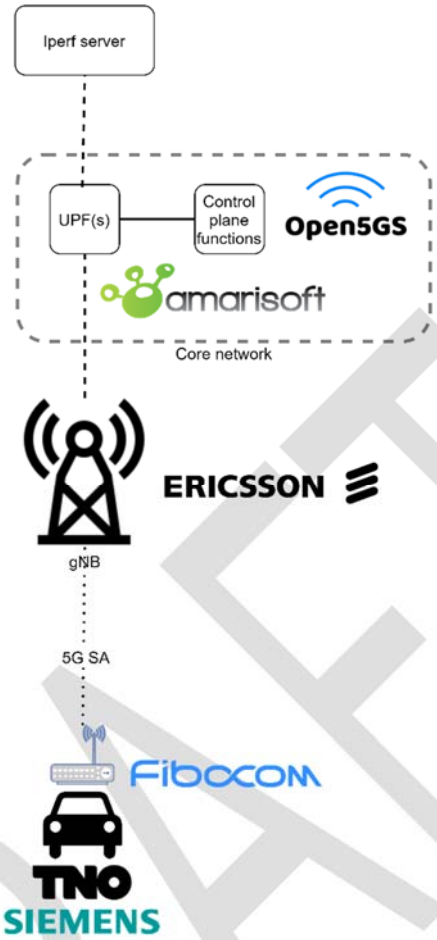

Figure 123: Test setup

Below table shows agnostic measurements results for the latency (RTT) and the maximal achieved throughput. The measurements are done with a single UE and with no other UE's on the 5G network.

Latency (edge routing)

RTT min (ms)	RTT avg (ms)	RTT max (ms)
5,801	8,533	16,791

Latency (core routing)

RTT min (ms)	RTT avg (ms)	RTT max (ms)
11,059	13,88	27,17

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Throughput

Method	Throughput min (Mbits/s)	Throughput avg (Mbits/s)	Throughput max (Mbits/s)
Iperf-down (TCP)	**122**	**443**	**571**
Iperf-down (UDP)	**388**	**437**	**513**
Iperf-up (TCP)	**41,9**	**52,5**	**66,5**
Iperf-up (UDP)	**48,6**	**55,5**	**67,5**

ExSe (Extended Sensors) application

The aim of the ExSe merging/lane changing application is to allow for a safe lane-change or merging action on the A270 road by extending, or in this case adding, object awareness to a vehicle. Below figure illustrates three vehicles: Siemens (equipped with sensors and the 5G SA OBU), TNO (equipped with the 5G SA OBU) and a passing vehicle (no equipment). The goal is to merge the TNO vehicle safely into the left hand lane, between the Siemens and the passing vehicle.

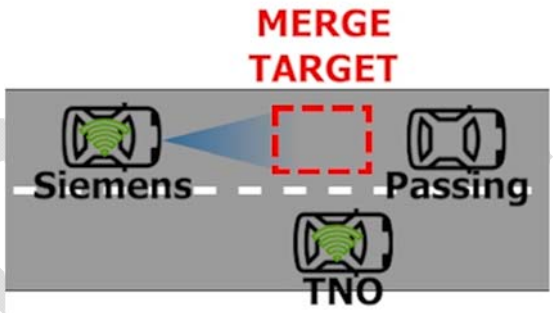

Figure 124: Use-case goal

Below figure shows the merging application on the smartphone HMI (left) and the camera views from the vehicles participating (right). A merge advice can be seen on the HMI, indicated by the white arrow ( ). The black (ego) position on the map-view represents the TNO vehicle, the red (CPM) position represents the passing car, the blue (CAM) position represents the Siemens vehicle.

Figure 125: Merge/lane change advice

Once the passing car is too close to the TNO vehicle for a safe merge, the merge advice will be removed until the passing car is at a safe distance from the TNO vehicle. This can be seen in below figure.

Figure 126: merge/lane change advice removed

5.3.3.2. *TU/e-AIIM vehicle & SISSBV OBU*

In the TU/e-AIIM vehicle as well as the SISSBV vehicle, the main vehicle PC is connected to the CAN-bus of the vehicles for data from the vehicle ECU. Both vehicles use a DrivePX2 with 4 cameras for the remote driving functionality, which in turn is connected using UDP to the vehicle PC.

For the remote driving function, TU/e-AIIM and SISSBV vehicles both use a KPN provided 5G modem from Ericsson, see Figure 127:

Figure 127: (left) TU/e-AIIM vehicle showing integrated OBU with 5G modem; (right) SISSBV vehicle showing integrated OBU with 5G modem

For the Advanced Driving user story, VTT is developing a 5G based OBU that will be integrated with the TU/e-AIIM vehicle (see sub-section)

On TU/e side, development showing live video (as tested early on in 5G-MOBIX, see section hereafter), including additional sensor information such as LIDAR is progressing (see Figure 128). Further development on combining live video (as shown in Figure 130) with the LiDAR detection and localisation is still in progress.

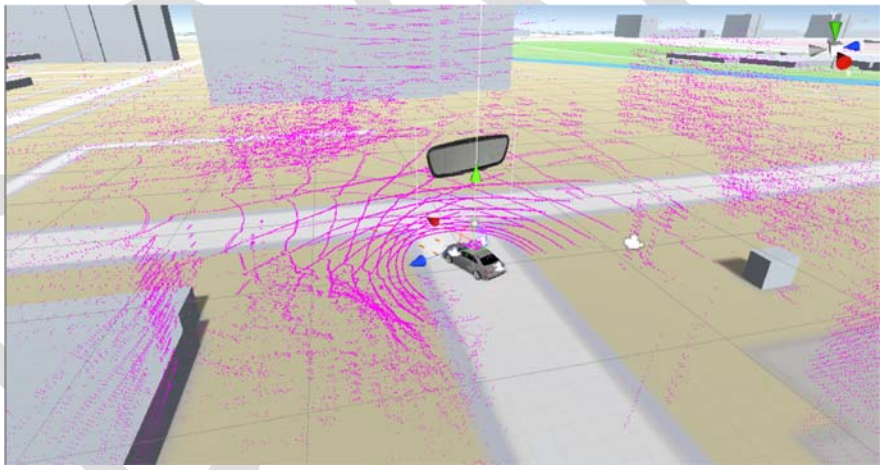

Figure 128: The LiDAR points as seen from the virtual visualisation scene on TU/e remote station (development status). This is used to aid the remote driver

Additionally, for the 5G positioning using mmWave, TU/e is developing its own OBU for testing on the TU/e network. This setup is tested in lab environment and currently tests are planned for outside.

In all cases, a 10Gbit Ethernet switch is integrated into the TU/e-AIIM vehicle for integration with each of the communication modules. These can and will be interchanged between tests, in order to prevent any unintended interference on antenna frequencies or on power supply during testing.

5.3.3.3. VTT vehicle OBU

The VTT OBU consists of a PC, connected to a 5G modem, GNSS receiver and power. The OBU, integrated in the vehicle, is shown in Figure 129. VTT has developed also a version of the on-board unit, which will be placed in other vehicles during the 5G-MOBIX tests, such as TU/e connected vehicle for CoCA tests in Helmond, VTT's motorcycle in Tampere and in CTAG's vehicles for the Cross-border contribution of the Dutch test site (overtaking maneuver with MCS), as well as in rental vehicles.

For the tests in Tampere the Huawei CPE 5G Pro router is used, which according to the specifications is suited for both NSA and SA networks. However, this modem could not connect to neither the Dutch or the Spanish networks. In the Netherlands a Netgear Nighthawk M5 5G modem is used, and in the ES-PT CBC a Xiaomi Mi 11 phone is used.

The on-board unit transmits and receives MCM (Maneuver Coordination Messages). Trajectories are calculated based on previous recorded vehicle paths. Potential warnings are shown on the PC display.

Figure 129: VTT OBU integrated in the trunk of the prototype vehicle Martti

5.3.4. Communication test results KPN network

For the remote driving User Story, early tests took place in January 2020, testing both the SISSBV and TU/e remote station and SISSBV and TU/e vehicle on the KPN network and showcasing this in a demo during the KPN 5G FieldLab event in Helmond. During the PO review on 3 December, KPN, TU/e, SISSBV, AIIM and associate partner Roboauto, showed a working demo, using 1 remote station and 2 vehicles over the KPN 5G SA network, proving the remote driving function to be working as expected and integration of the OBU in the vehicles to be ready. A video recording can be found on the 5G-MOBIX website[12], showing the results of the first test.

[12] https://5g-mobix.com/hub/5g-mobix-demo-remote-driving

After that first test, 2 additional trials were executed on Vaarle near A270 between Helmond and Eindhoven. (See also Figure 130). A video showcasing these driving tested is also published online on LinkedIn: https://www.linkedin.com/posts/josdenouden_5g-mobix-vaarle-activity-6785602446463922177-lgZ5

Figure 130: Screenshot of TU/e-AIIM and SISSBV vehicles remotely driven over KPN 5G SA network during trials in March-April 2021 and September 2021

Latency tests were executed that and remote driving tests were done using straight line braking and slalom tests. These will be further described in WP4 deliverables D4.3. Network tests were executed, with Figure 131 showing the latency differences between 4G and 5G for video uplink, control uplink and control downlink, using the KPN provided 5G modems as described in section "TU/e-AIIM vehicle & SISSBV OBU" above.

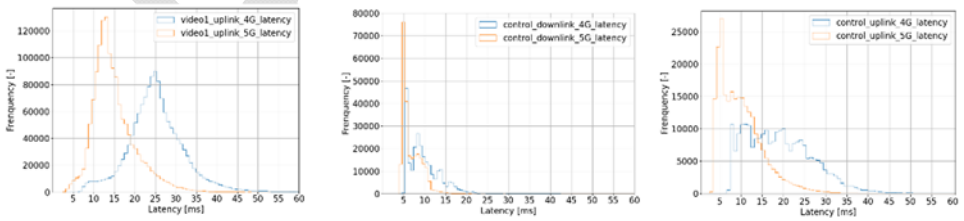

Figure 131: Histogram of measured latencies (in [ms]) on 4G vs. 5G network for video uplink (a), control downlink (b), control uplink (c)

5.4. FR Setup

5.4.1. Sensors & devices integration

Since 2014, the VEDECOM has been working on automated vehicles and developed its perception and automated driving functionalities based on carefully selected vision and touch sensors. In 5G-MOBIX, the FR TS is exploiting the earlier experiences of VEDECOM by using the vehicle with the same set of sensors (RADAR, LiDARs, cameras, GNSS, fusion box as listed in Table 16 as described in D2.4 (1)). In the project, the main efforts have been made for integration of 5G OBU in the vehicle, implementation of communication stack and applications to realise the FR TS use cases and measurements

Table 16: Overview of devices integrated in FR vehicle

Type of Sensor	Units	Model	Characteristics
RADAR	1	ARS 408	0.20 ...250 m far range,
LiDAR	5	Velodyne	360° perception
Camera	2	Stereo camera	Front and back cameras
GNSS	1	Geoflex	RTK GPS receiver
Fusion	1	IBEO	Fusion box
Communication	1	VEDECOM OBUS (SIMcom shipset) VALEO OBU	5G -OBU
Ethernet switch	1		
PC	3	1 Nexcom 1 Nexcom 1 dSPACE	PC Camera Perception PC

The vehicle integration is completed and is done with the collaboration of the connectivity and vehicle automation teams in order to offer the required interfaces to let all these sensors communicate with the 5G-OBU. Interfaces with the 5G-OBU and the internal PC are also defined in order to provide a harmonized data

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format and to facilitate integration. This communication interface is now validated and tested. Figure 132 and Figure 133 below depict the sensors integration architecture inside the Zoe vehicle.

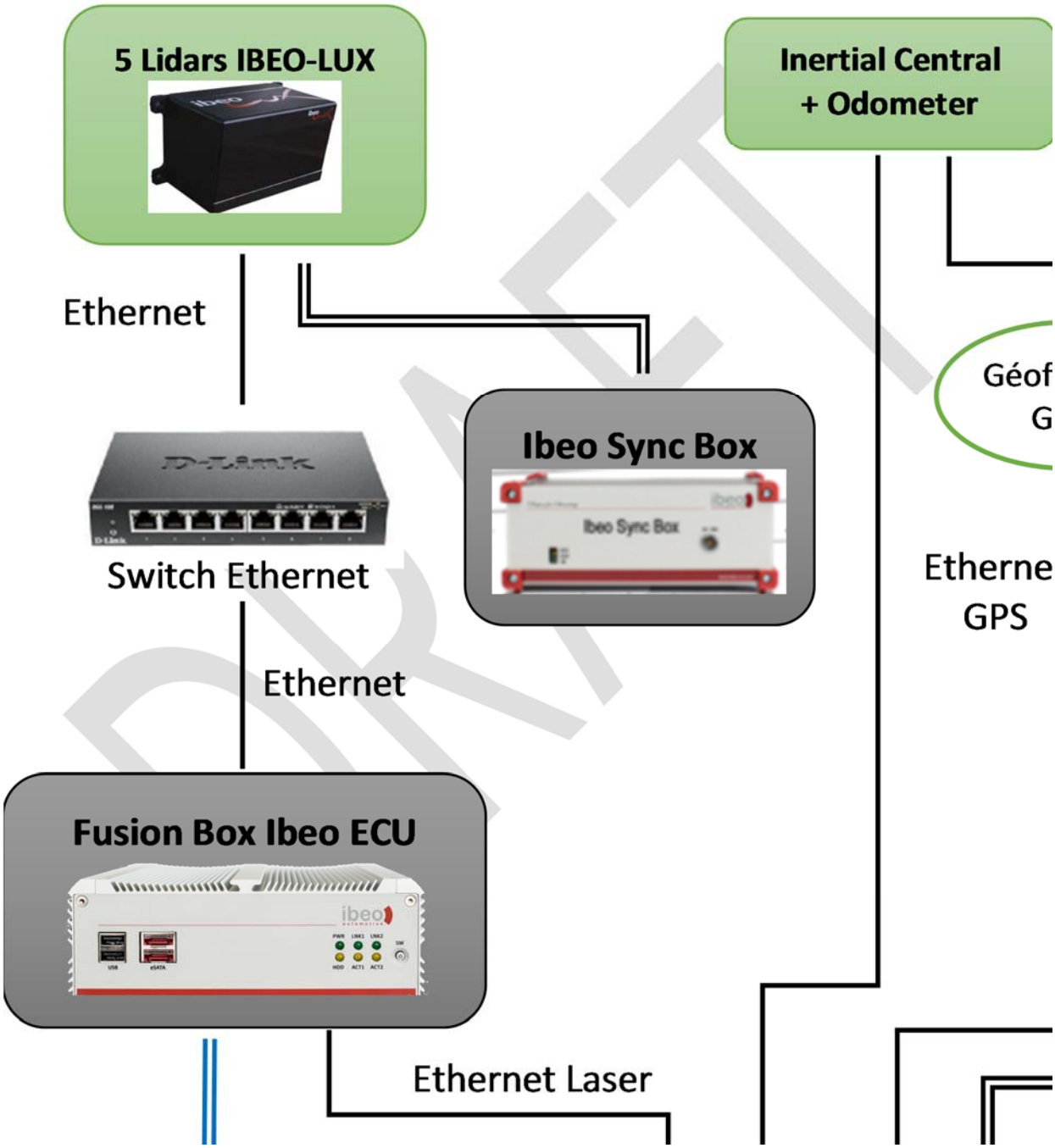

Figure 132: FR TS Vehicle Zoe: Sensors integration

Figure 133: Distribution of the devices in the vehicle

5.4.2. Automated driving function development

To carry out the trials for the User Story infrastructure-assisted advanced driving, automated driving functions had to be adapted to support the introduction of 5G technology and also the information that will come from the infrastructure to extend its perception or also requesting advanced manoeuvre.

To this end, the module related to lateral path planning is adapted to be able to receive requests for lane change manoeuvre from an external entity (infrastructure) and execute the command if possible, taking into account its own environment of perception.

Another module was introduced which will offer the connection with the 5G-OBU; this is an evolution of the 4G module already in place. It will offer the required interfaces and APIs to communicate with the 5G-OBU. An overview of AD modules can be consulted in Figure 134.

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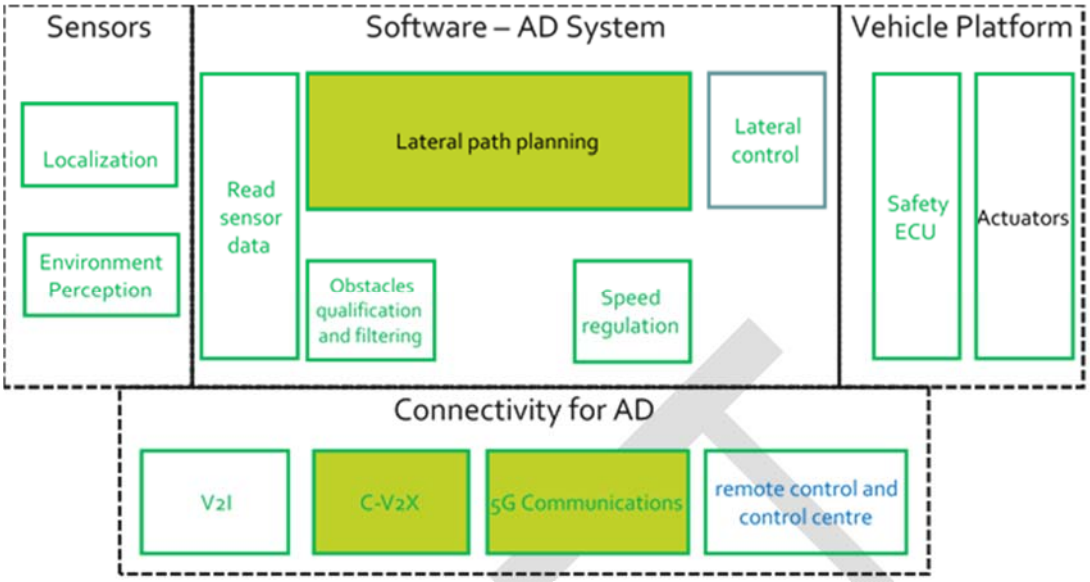

Figure 134: Automated driving functions overview

5.4.3. OBU integration

5.4.3.1. FR communication unit set up

FR TS will use 2 types of OBUs:

- VEDECOM made 5G OBUs: based on SimCOM modems. These 2 OBUs are ready and were already tested on the 5G network of Bouygues.
- 3x VALEO 5G OBUs: based on Qualcomm chipsets. These OBUs are still on the delivery process and were not yet received by the FR TS.

The 2 5G modems (SimCom8200), presented in Figure 135, allow the communication box to be attached at 2 different MNO at once and to be connected on the best vector of communication.

The SIM8200-M2 series is the Multi-Band 5G NR/LTE-FDD/LTE-TDD/HSPA+ module which supports R15 5G NSA/SA up to 4Gbps data transfer. It has strong extension capability with rich interfaces including UART, PCIe, USB3.1, GPIO etc. The module provides much flexibility and ease of integration for customer's application.

The SIM8200-M2 series adopts the M.2 form factor, TYPE 3052-S3-B. AT commands of SIM8200-M2 series are compatible with SIM7912G/SIM8300G-M2 series modules. This also minimizes the investments of customers and enables a short time-to-market.

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It is designed for applications that need high throughput data communication in a variety of radio propagation conditions. Due to the unique combination of performance, security and flexibility, this module is ideally suited for many applications.

Figure 135: SIM8200-M2 5G modem

In the following Figure 136, we highlight the use of M.2 to mPCIe adapter in order to connect the 5G modem to the OBU board.

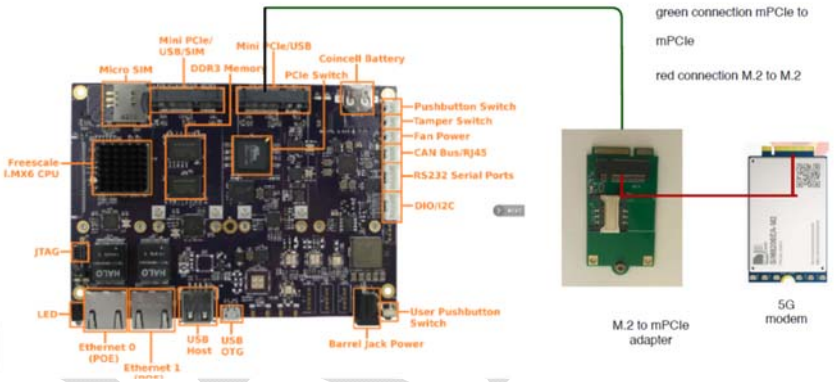

Figure 136: SimCOM 8200 connection to the board using M.2 to mPCIe adpater

5.4.3.2. 5G OBU Board

One of the gigabit Ethernet interfaces will be used to connect to the Pepwave device which will handle the intelligent routing. This device will monitor all means of communication and will decide for the handover between technologies like 5G to 5G or 5G to satellite. The other Gigabit Ethernet port will be connected to the internal PC which will be in charge of handling the sensors in the vehicle.

In the following table, we describe the different components on the 5G-BOX at its current phase, including the 4G, 5G and 11 p technologies.

Table 17: Components on the 5G BOX

Technology	Driver modification	Kernel modification	Recognized on the OBU	Connectivity	Tests
4G	Yes	Yes	Yes	Yes	done
5G (1st modem)	Yes	Yes	Yes	Yes	done
5G (2nd modem)	Yes	Yes	Yes	Yes	done
11p	Yes	Yes	Yes	Yes	done

The Figure 137, highlights the different components of the board. The components are the following:

- (1) Bouygues sim card,
- (2) 5G modem,
- (3) 5G antennas connected to the modem,
- (4) Ethernet cable connected to PC, using the OBU as a gateway,
- (5) Jtag connector to flash image from PC to board and connect to board also

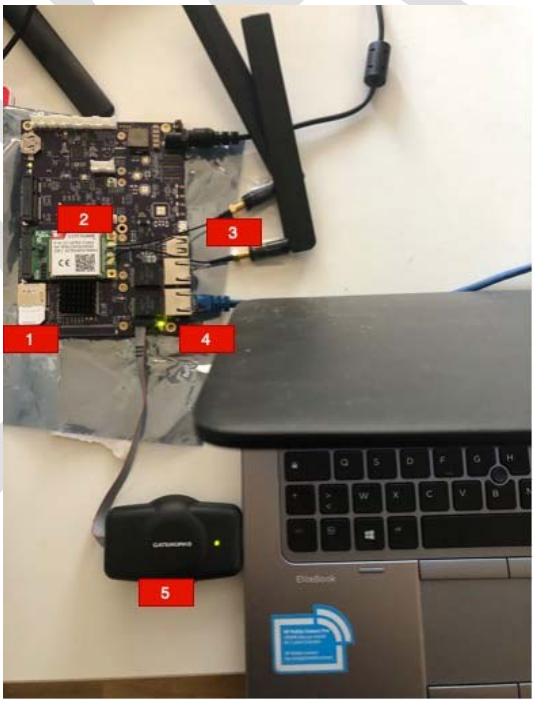

Figure 137: VEDECOM 5G OBU components

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5.4.3.3. Pepwave device integration

In the FR-TS, a Commercial Off the Shelf (COTS) routing device equipped with mode switching and RAT bonding capabilities, will be integrated with the OBU. The OBU is connected through the router's LAN interface and the router is configured with two wide area network (WAN) interfaces. The WAN interfaces will be connected to the dual-SIM 5G OBUs (or two OBUs) to test FR TS's multi-SIM/multi-PLMN solution. In this setting, the intelligent router allows the UE to keep connections with multiple PLMNs to ensure continuity with the application endpoint (in the cloud or in the MEC). Depending on the policy set by the user, the router can actually use only one of the two interfaces depending on the priority level, quality of the end-to-end flow (shortest delay, highest throughput), or the signal quality. It is also possible that the router uses the two interfaces with link aggregation functionality. In this case, the end-to-end connection can benefit increased throughput and seamless connectivity.
The intelligent router will also be used to test the benefits/drawbacks of satellite connectivity particularly in area with no coverage. When it comes to testing the Satellite connectivity, one of WANs will be connected to 5G OBU and another to satellite Low Earth Orbit (LEO) connectivity as illustrated in Figure 138.

To terminate the VPN connection, another intelligent router, with flow aggregation functionality, is required at the server site, where the CCAM application is installed. Different servers (speed fusion boxes) were installed. One is at Catapult's 5G step out centre facility, in Oxfordshire, UK, where FR TS's cloud application modules are installed. The second server is at the VEDECOM institute, in Versailles, France close to the test area.

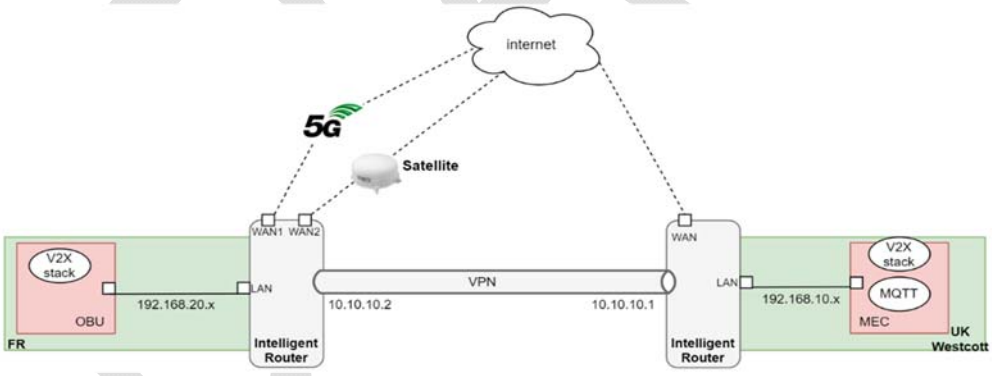

Figure 138: FR TS Pepwave device integration

5.4.4. Early testing results

Two validation phases are considered in the following: laboratory validation and closed-circuit validation.

5.4.4.1. Laboratory validation

The objective of this step is to approve the output of the system before testing it on a closed circuit or on an open road.

5G connectivity:

As the two 5G OBU made by VEDECOM were ready by the end of September, VEDECOM carried out a first testing session with Bouygues 5G network in lab conditions. The main goal of this test was to see if the 5G connectivity will work as it's the first time FR TS will test its OBU. Hence, the 5G connectivity test was successful and the board got connected right on the start-up is illustrated by Figure 139.

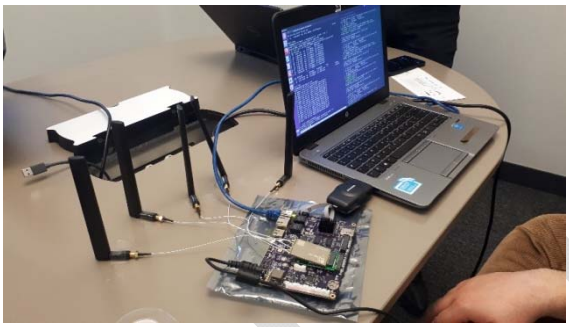

Figure 139: VEDECOM 5G OBU testing with Bouygues 5G network

During these tests, we managed also to test the latency, throughput and other parameters related to the modem and operator as illustrated by Figure 140.

```
+CGPS: 0
at+cpsi?
+CPSI: LTE,Online,208-20,0x76E9,129550855,482,EUTRAN-BAND20,6200,3,3,-63,-706,-472,19
+CPSI: NOT IN EN-DC CONNECTED MODE

OK
at+cpsi?
+CPSI: LTE,Online,208-20,0x76E9,129550852,482,EUTRAN-BAND7,3175,4,4,-65,-864,-611,24
+CPSI: NR5G,480,650592,-11,-68,22.0
```

Figure 140: VEDECOM 5G OBU: modem and operator parameters measurement

The results of throughput in DL and UL were unsatisfactory as depicted by Figure 141.

```
root@OpenWrt:/# iperf3 -c bouygues.iperf.fr -p 5200
Connecting to host bouygues.iperf.fr, port 5200
[  4] local 10.51.149.189 port 36382 connected to 89.84.1.222 port 5200
[ ID] Interval           Transfer     Bandwidth       Retr  Cwnd
[  4]   0.00-1.00   sec  5.02 MBytes  42.1 Mbits/sec    1    197 KBytes
[  4]   1.00-2.00   sec  5.09 MBytes  42.7 Mbits/sec    0    214 KBytes
[  4]   2.00-3.00   sec  5.00 MBytes  41.9 Mbits/sec    0    230 KBytes
[  4]   3.00-4.00   sec  5.30 MBytes  44.4 Mbits/sec    0    246 KBytes
[  4]   4.00-5.00   sec  5.06 MBytes  42.5 Mbits/sec    0    259 KBytes
[  4]   5.00-6.00   sec  4.70 MBytes  39.5 Mbits/sec    0    279 KBytes
[  4]   6.00-7.00   sec  4.90 MBytes  41.1 Mbits/sec    0    339 KBytes
[  4]   7.00-8.00   sec  5.45 MBytes  45.7 Mbits/sec    0    418 KBytes
[  4]   8.00-9.00   sec  5.19 MBytes  43.6 Mbits/sec    0    511 KBytes
[  4]   9.00-10.00  sec  5.50 MBytes  46.1 Mbits/sec    0    649 KBytes
```

Figure 141: Measured Throughput within Bouygues 5G network

In fact, the DL throughput calculated was equal to 35 Mbps. On the other side the UL throughput was equal to 45 Mbps. Using a 5G phone provided by Bouygues, the DL throughput of the 5G phone was equal to 600 Mbps.

An investigation was carried out to figure out why the throughput measured by the 5G-OBU is lower than expected. The results have confirmed that the use of M.2 to MPCIe adapter is behind the throughput decrease. In fact, the OBU without the adapter with a mPCIe 2.0 interface can achieve up to 5 Gbps, but when the adapter is installed it limits the throughput to 4.8 Mbps which converts to roughly ~ 60 Mbits/s. To solve the issue, we have changed the adapter by a new USB3 M.2 to MPCIe adapter.

Additional testing has been carried out to investigate the latency measurements. The latency calculated using the ping command has led to the following result: **10 ms (one way).**

Validation of the intelligent router

We conducted tests of Pepwave, which will be used for multi-SIM/multi-PLMN solution for Bouygues and Orange networks. As can be seen in the image below, the functionalities of the intelligent router, particularly interfaces selection and link bonding, have been validated.

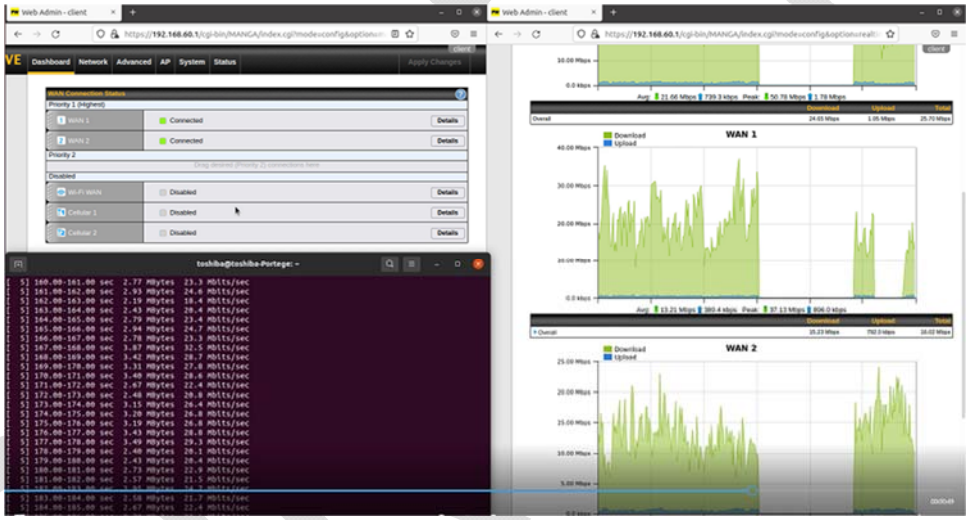

Figure 142: Validation of the intelligent router

C-ITS modules

In the following Table 18 and Table 19, the different conducted tests to validate the OBU C-ITS modules are presented.

Table 18: Test result for C-ITS modules

Environment: **VEDECOM Laboratory**		
Components: **OBU C-ITS module**		
TEST ID	**TEST PURPOSE**	**RESULT**

OBU-CAM01	Test that the **OBU CA Server** is able to generate and broadcast CAM .	**Validated**
OBU-CAM02	Test that the **OBU CA Client** is able to receive CAM	**Validated**
OBU-MCM01	Test that the **OBU MC Client** is able to receive MCM messages without trajectory guidance	**Validated**
OBU-MCM02	Test that the **OBU MC Client** is able to receive MCM messages with trajectory guidance container. The message is relevant i.e., the vehicle is the destination of the trajectory guidance.	**Validated**
OBU-CPM01	Test that the **OBU CP Server** is able to generate and transmit CPM messages.	**Validated**
OBU-CPM02	Test that the **OBU CP Client** is able to receive CPM messages sent by a MEC.	**Validated**
OBU-CPM03	Test that the **OBU CP Client** is able to receive CPM messages sent by a vehicle.	**Validated**
OBU-MAP01	Test that the **OBU MAP Client** is able to receive MAP msg.	**Validated**

Perception modules

Table 19: Test result for perception modules

Environment: **VEDECOM Laboratory**		
Components: **Vehicle perception module**		
TEST ID	**TEST PURPOSE**	**RESULT**
OBU-PER-L01	Test that the **OBU Local perception module** is able to detect a vehicle driving in a targeted lane.	**Validated**
OBU-PER-A01	Test that the **OBU Fusion module** is able to provide a list of objects when no V2X communication exists.	**Validated**
OBU-PER-A02	Test that the **OBU Fusion module** is able to provide a list of objects when no local perception exists	**Validated**
OBU-PER-A03	Test that the **OBU Fusion module** is able to add an object detected by the local perception system to its list of objects when no V2X communication data exists	**Validated**
OBU-PER-A04	Test that the **OBU Fusion module** is able to add an object to its list of objects based on CAM data when no local perception information is available	**Validated**
OBU-PER-A05	Test that the **OBU Fusion module** is able to associate a CAM Data with an existing object that has been detected by the local perception	**Validated**

5.4.4.2. Field test results

Tests have been carried out in story site to test different functionality related to the OBU (connectivity+ perception).

As it is shown in the Figure 143, we have validated CAM, CPM and MCM messages exchanges between vehicle and MEC (vehicle to vehicle via MEC). Particularly, as the AV was heading towards the intersection, the MEC has assessed that there is a potential collision risk with the basic vehicle, and then an MCM message was sent to the AV. In the right screen of the figure, the OBU is receiving an MCM with the required information regarding the lane change manoeuvre and with also the required speed. The reception of MCM message was then validated in field test conditions.

Figure 143: MCM reception inside the AV

During the tests, we have measured throughput of individual messages as illustrated in the figure below.

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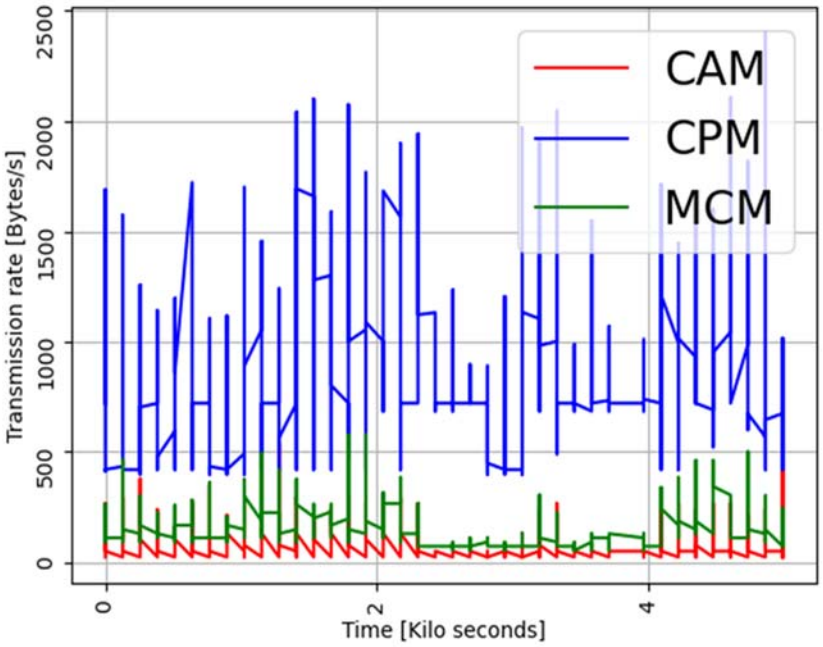

Figure 144: CAM, CPM, and MCM data rate

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5.5. CN Setup

CN site has two sections Jinan-1-SDAS and Jinan-2-SDHS for three UCs. Jinan-1-SDAS was deployed with a 5G shared MEC solution provided by China mobile. And Jinan-2-SDHS was deployed with a 5G SA solution by China Unicom. Two 5G MNOs were employed to simulate the CBC problems (XBI_4 Low coverage Areas, etc.), which are solved with CS-4 (Multi-modem / multi-SIM connectivity) and CS-11 (Double MQTT client).

CN site employed two 5G MNOs to simulate the CBC problems. We learned different 5G business plans with 5G features and the corresponding costs to deploy them. There are three big 5G MNOs in China: China Mobile, China Unicom, and China Telecom. They provide various 5G business plans, which can be roughly divided as (a1) 5G standalone Non-Public Network with specific frequency and high security; (a2) Public Network Integrated Non-Public Network with public frequency and low latency; (a3) Public network with shared MEC for end-to-end QoS and low latency guarantee.

The a1 plan is very expensive and suits big enterprises, and the a2 plan is suited for the CN site for testing our UCs. The MNOs informed that additional network service host systems would need to be acquired as well as some construction for MEC service, which will first cost about 500,000 RMB (69,958EUR). The CN site had to choose the a3 plan with 5G shared MEC for the limited budget.

5.5.1. Sensors & devices integration

The CN TS vehicle will be equipped with the sensors described in D2.4(2) and Table 20 for testing the User Stories.

Table 20: Devices integrated in CN vehicle

Type of Sensor	Units	Characteristics	Additional info
Camera	1	Monocular camera	Dedicated image sensors of PointGray
RADAR	1	mmWave RADAR	One Delphi RADAR of 24 GHz
LiDAR	1	Multi-line LiDAR	Three Velodyne LiDARs, one of 32-line, two of 16-line
Navigation	1	Integrated navigation	One Trimble GPS
Computer	2	High-performance computer	Inter® i7-7700T, Intel Q170 Chipset, 2x DDR4 16G CPU of YANHUA
Operating System	1	Ubuntu 18.04	
Autoware System	1	Type of proposal	
Ros System	1	Ros2	

These devices were selected for the following reasons:

- The advantage of LiDAR is that it has a long detection distance and can accurately obtain three-dimensional information of objects. In addition, it has high stability and good robustness.
- The advantages of millimetre-wave RADAR are high resolution and small size. The antenna and microwave components of the millimetre-wave RADAR can be small, and the small antenna size can obtain a narrow beam. Distance and speed information can be measured directly.
- The camera can identify vehicles, pedestrians, lanes, road signs, traffic signs, traffic lights and so on in the vehicle driving environment, and has high image stability, anti-interference ability and transmission ability. As a common vehicle sensor, the advantage of the camera is that it can distinguish colours and is more suitable for scene interpretation.
- The advantages of intel processors are high performance, low power consumption, stability, low temperature, advanced architecture, and some processors support hyper-threading to simulate multi-core.
- The advantage of Ubuntu's operation synergy is that it is an efficient file management system and generally does not require defragmentation. There is very little system garbage generated, and the system will not become more and more stuck with the increase of use time. The system is safe and stable, the bugs are repaired quickly, and there are few viruses. Permission management is very strict to avoid user disoperation. Copy files fast.
- Autoware is the world's first "customized" opensource software designed to drive cars. The function of Autoware is mainly suitable for cities, but "expressways and municipal roads can also make". At the same time, it can provide rich development and enabling resources on the Autoware mobile driving opensource software built by ROS.
- The advantage of the ROS system is that the development language of ROS is independent. It Aggregates a large number of opensource function packages implemented by developers around the world. The system structure design is quite distinctive. The ROS runtime is composed of multiple loosely coupled processes. Each process in ROS is called a node. All nodes can run on one processor or distributed in multiple on the processor.

The environment perception is mainly machine vision, RADAR, V2X, and other environmental perception theory, algorithm verification, and environmental simulation tests. The modeling and simulation analysis, hardware theory research, and various environmental sensing technologies aim to provide a basis for intelligent network vehicle research. The research mainly adds actuators to complete the power, braking, steering control, and other vehicle functions.

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5.5.2. Automated driving function development

The Cloud-assisted advanced driving functions have been adapted according to the illustrations below for testing the User Stories.

5.5.2.1. User Story #1: Cloud-assisted advanced driving

In this case, we employ the SDIA vehicle to test the scenario, shown in Figure 145.

Figure 145: CN vehicle

Due to the fast-change situations on the road, all perception-related processing of vehicles is time-critical, which have the following functions:

- The SDIA Vehicle can collect sensor data and contact with each other by V2X Communication.
- Vehicles will monitor the road safety and dynamic control of its motion.

Also, another module was introduced which will offer the connection with the 5G-OBU; this module is an evolution of the 4G module already in place. This module will offer the required interfaces and APIs to communicate with the 5G-OBU.

Figure 146 presents an overview of the AD functions for CN vehicle:

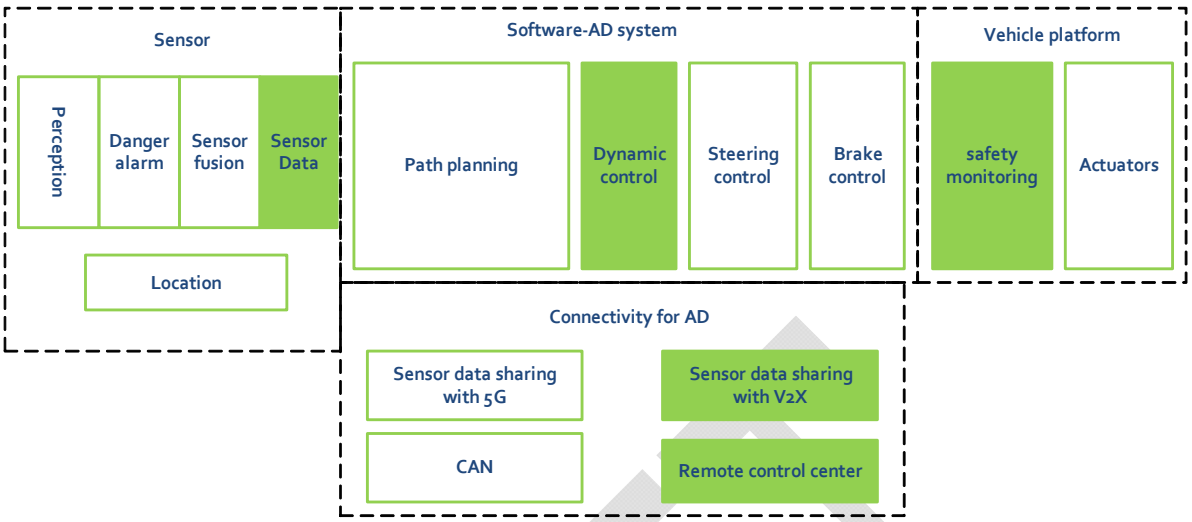

Figure 146: Automated driving functions overview

5.5.2.2. *User Story #2: Cloud-assisted platooning*

In this story, V2X road safety services are applied to traffic systems through roadside units (RSUs). RSUs generate and distribute traffic safety-related messages for road safety and deliver them to vehicles equipped with onboard units (OBUs). In this case, safety information at the intersection involves precise digital maps, traffic signal information, pedestrian and vehicles' moving status information, and location information, which is generally expressed in LDM (Local Dynamic Map). The 3GPP system will support an average of 0.5 Mbps in downlink and 50 Mbps in the uplink. An RSU will communicate with up to 200 UEs supporting a V2X application. Also, RSU will support 50 packet transmissions per second with an average message size of 450 bytes.

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Figure 147: Cloud-assisted platooning

5.5.2.3. *User Story #3: Remote driving with data ownership focus*

Remote driving is a very demanding task for connectivity. The situational awareness from a multitude of data-rich sensor needs to be transferred to the remote location. The remote operator needs to be brought quickly up the current moment despite even long periods of inactivity. Therefore, the flow of the User Story is as follow in Figure 148:

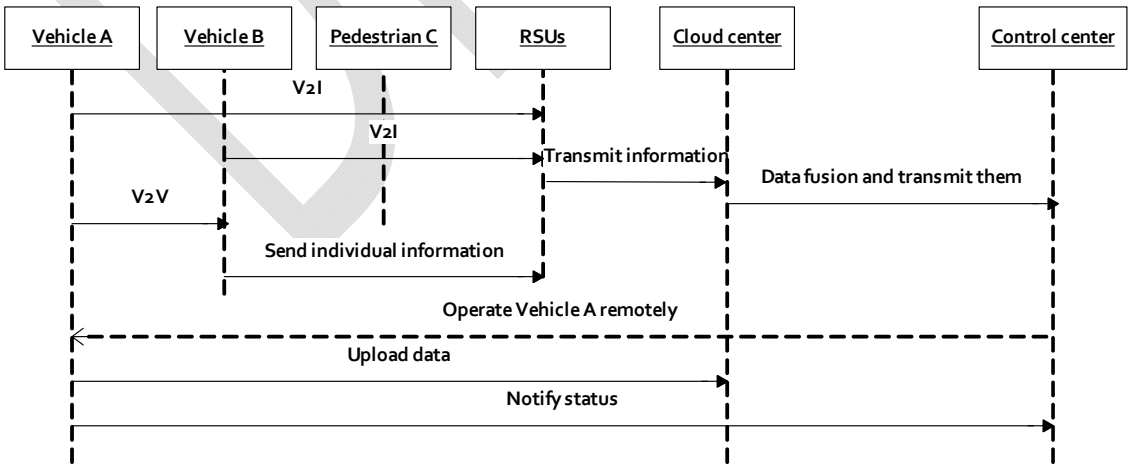

Figure 148: UC messages flow

We tested the remote driving scenario and achieved phased results. The following Figure 149 shows the control terminal is remotely controlling the vehicle during the remote driving test.

Figure 149: Remote driving control terminal

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5.5.3. OBU integration

We used the SIM8200EA-M2 to establish communication between the test vehicle and the system. The SIM8200EA-M2 is a multi-band 5G NR/LTE-FDD/LTE-TDD/HSPA+ module solution that supports R15 5G NSA/SA data transmission to 4.0 Gbps. The module had powerful expansion capabilities and rich interfaces, including PCIe, USB3.1, GPIO, etc. Simultaneously, the module could provide a range of spectrum to help us test even more complex communication scenarios in the future, whose spectrum is shown in Table 21.

Table 21: Spectrum supported by SIM8200EA-M2

5G NR	**n1,n2,n3,n5,n7,n8,n12,n20,n25,n28,n40,n41,n66,n71,n77,n78,n79**
LTE-TDD	B1/B2/B3/B4/B5/B7/B8/B12/B13/B14/B17/B18/B19/B20/B25/B26/B28/B29/B30/B32/B66/B71
LTE-FDD	B34/B38/B39/B40/B41/B42/B43/B48
WCDMA	B1/B2/B3/B4/B5/B8

In Figure 150 the SIM8200EA-M2 can be seen.

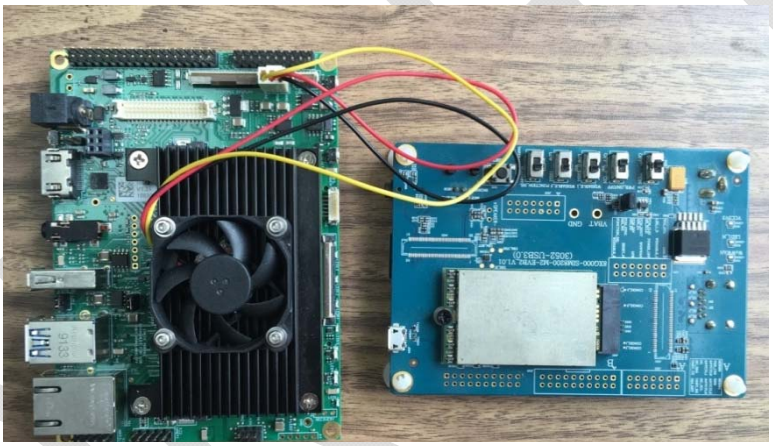

Figure 150: SIM8200EA-M2

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We deployed the module on our test vehicle, provided by CHNTC. We have also connected the SIM8200EA-M2 and OBU to supply Uu connection for V2I and V2V (see next figure

Figure 151).

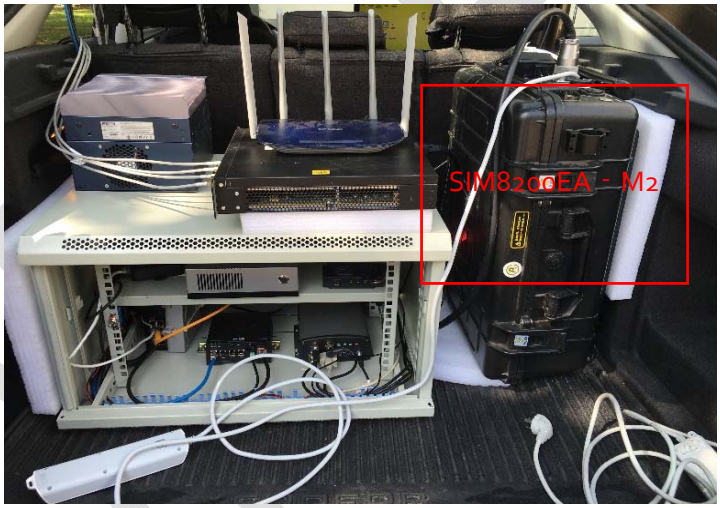

Figure 151: OBU equipment in vehicle

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5.5.4. Early testing results

Figure 152: Early test of OBU

The early tests evaluated simple connectivity Figure 152(). the two 5G OBU made by Cohda were ready by the end of September. The main goal of this test was to see if the connectivity would work. Hence, the connectivity test was successful and the board was connected right on the start-up.

We also test the Device-to-Device Connection. Two sets are used, one of them is configured as Main device and the other one is set as from device. The MAC address must be different.

- Main device: Input: bt_mast.sh init "02 44 32 AA 47 61"
- From device: input: bt_slave.sh init "01 44 32 AA 47 61"

The result is shown in Figure 153.

```
1999-11-30 02:03:19.307 I v2x_log.c:672: app log start, log file: /mobilelog/v2x//v2xmaster.log, l
og backUp file: /mobilelog/v2x//v2xmaster.old.log, log mask: 3, log file num: 5, log max size: 104
8576

V2xSdkInit result ret: 0
V2xAccessDataRecvRegister result ret: 0
1999-11-30 02:03:19.307 I v2x_ipc_client.c:351: Connect Server: /var/run/v2x_stack_socket, Get ind
ex: 0
1999-11-30 02:03:19.307 I v2x_ipc_client.c:190: connect server success, clientFd: 6
1999-11-30 02:03:19.308 I v2x_ipc_common.c:110: add type: 3
1999-11-30 02:03:19.308 I v2x_ipc_common.c:37: request type: 97, reqData: 1234
1999-11-30 02:03:19.308 I v2x_ipc_client.c:319: V2xIpcClientEstablishConnection success
1999-11-30 02:03:19.508 I v2x_ipc_common.c:37: request type: 98, reqData: 6
1999-11-30 02:03:19.508 I v2x_ipc_client.c:464: v2x ipc register msg cb success
1999-11-30 02:03:19.508 I v2x_ipc_common.c:37: request type: 98, reqData: 8
1999-11-30 02:03:19.508 I v2x_ipc_client.c:464: v2x ipc register msg cb success
1999-11-30 02:03:19.508 I v2x_ipc_common.c:37: request type: 98, reqData: 3
1999-11-30 02:03:19.508 I v2x_ipc_client.c:464: v2x ipc register msg cb success

master local MAC : 00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
send data: master msg from MAC:00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
send data: master msg from MAC:00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
send data: master msg from MAC:00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
send data: master msg from MAC:00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
send data: master msg from MAC:00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
send data: master msg from MAC:00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
send data: master msg from MAC:00 11 22 33 44 55
recv access data: slave msg from MAC:AA BB CC DD EE FF
```

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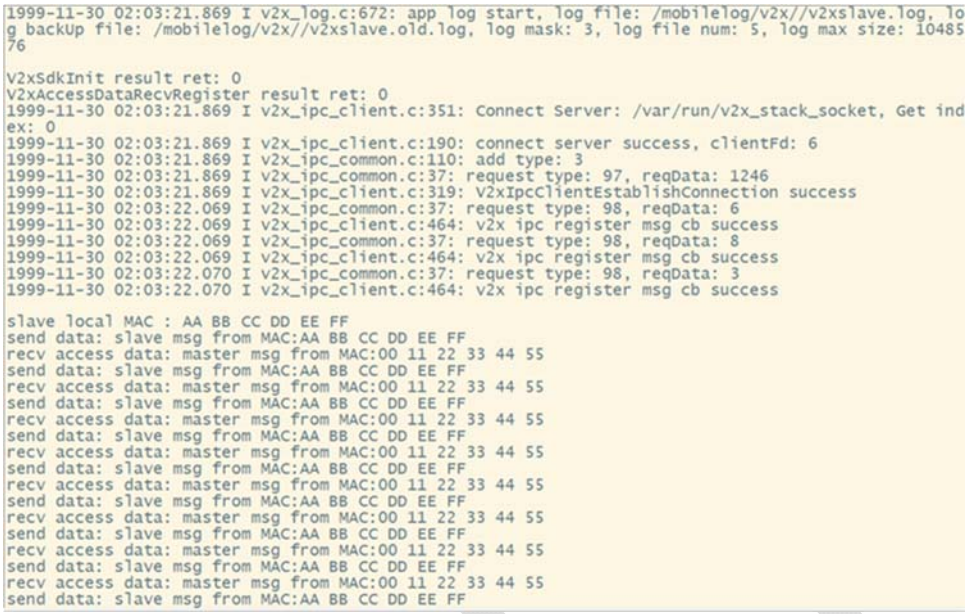

```
1999-11-30 02:03:21.869 I v2x_log.c:672: app log start, log file: /mobilelog/v2x//v2xslave.log, lo
g backUp file: /mobilelog/v2x//v2xslave.old.log, log mask: 3, log file num: 5, log max size: 10485
76

V2xSdkInit result ret: 0
V2xAccessDataRecvRegister result ret: 0
1999-11-30 02:03:21.869 I v2x_ipc_client.c:351: Connect Server: /var/run/v2x_stack_socket, Get ind
ex: 0
1999-11-30 02:03:21.869 I v2x_ipc_client.c:190: connect server success, clientFd: 6
1999-11-30 02:03:21.869 I v2x_ipc_common.c:110: add type: 3
1999-11-30 02:03:21.869 I v2x_ipc_common.c:37: request type: 97, reqData: 1246
1999-11-30 02:03:21.869 I v2x_ipc_client.c:319: V2xIpcClientEstablishConnection success
1999-11-30 02:03:22.069 I v2x_ipc_common.c:37: request type: 98, reqData: 6
1999-11-30 02:03:22.069 I v2x_ipc_client.c:464: v2x ipc register msg cb success
1999-11-30 02:03:22.069 I v2x_ipc_common.c:37: request type: 98, reqData: 8
1999-11-30 02:03:22.069 I v2x_ipc_client.c:464: v2x ipc register msg cb success
1999-11-30 02:03:22.070 I v2x_ipc_common.c:37: request type: 98, reqData: 3
1999-11-30 02:03:22.070 I v2x_ipc_client.c:464: v2x ipc register msg cb success

slave local MAC : AA BB CC DD EE FF
send data: slave msg from MAC:AA BB CC DD EE FF
recv access data: master msg from MAC:00 11 22 33 44 55
send data: slave msg from MAC:AA BB CC DD EE FF
recv access data: master msg from MAC:00 11 22 33 44 55
send data: slave msg from MAC:AA BB CC DD EE FF
recv access data: master msg from MAC:00 11 22 33 44 55
send data: slave msg from MAC:AA BB CC DD EE FF
recv access data: master msg from MAC:00 11 22 33 44 55
send data: slave msg from MAC:AA BB CC DD EE FF
recv access data: master msg from MAC:00 11 22 33 44 55
send data: slave msg from MAC:AA BB CC DD EE FF
recv access data: master msg from MAC:00 11 22 33 44 55
send data: slave msg from MAC:AA BB CC DD EE FF
recv access data: master msg from MAC:00 11 22 33 44 55
send data: slave msg from MAC:AA BB CC DD EE FF
```

Figure 153: Device to Device Connection Test

It adopts the vehicle standard high performance computing chip I.MX 8, supports Huawei 5G+V2X communication module MH5000, Beidou +GPS dual mode module, supports RTK high-precision positioning, supports CAN bus communication, and integrates driver monitoring system (DMS) and ADAS system to achieve low-cost vehicle-road cooperative equipment on expressways.

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Table 22: Spectrum supported by SIM8200EA-M2

Processor		
	Memory	2GB(LPDDR4)RAM+8GB EMMC
Air Interface	LTE	5G full netcom, vehicle standard LTE module, backward compatible with 4G/3G/2G network
	V2X	V2X UU、PC5 direct communication
	GNSS	Ordinary positioning ≤ 2.5m, RTK positioning ≤ 10cm (optional), support heading detection
	Antenna Interface	4G/5G Main Diversity Antenna, V2X Main Diversity Antenna, GNSS Antenna
Functional Interface	CAN	Support 1*CAN
	USB	Support 1*USB
	RS232	Support 1*RS232
	Ethernet	1 channel 10/100/1000M air plug interface
	HDMI	1 channel HDMI1.4 interface, support audio transmission
	SIM Card	1 standard SIM card slot
	TFCard	1 standard TF card slot
	audio port	Support 1*SPEAKER output
	Power interface	Support 1 channel 12V power output interface and 1 channel power input interface
Power Characteristics	Operating Voltage	9 - 36V，Typical input 24V
	Working current	≤2400mA@24V
		1500mAh, Wide temperature working battery
Physical Properties	IP rating	IP55
	Operating Temperature	-40 - 85℃
	Storage Temperature	-40 - 85℃
	Chassis size	215*135*45mm
	Material	Aluminum profile

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5.6. KR Setup

5.6.1. Sensors & devices integration

To carry out the user story (remote controlled vehicle via mmWave communication) testing and trialling, the KR TS vehicle equips with the following sensors and communication devices as can be consulted in Table 23.

Table 23: Vehicle equipment overview

Type of Sensor	Units	Characteristics	Additional info
RADAR	1	Front RADAR	Valeo, 77 GHz (70m~)
	2	Left/Right Side RADAR	Valeo, 24GHz
Ultrasonic	8	Front / Rear Ultrasonic Sensor	Valeo, 50kHz
Camera	4	HD camera	- Front, Left/Right and rear cameras
	4	HD Camera	- Around view camera (Front, Left/Right and rear) for 360 deg camera
	3	HD Camera	Front and rear scene recording Driver recording scene camera
GNSS	1	DGPS	less than 10cm
Speed Sensor	1	Vehicle Speed	N/A
	1	Displayed Speed (Cluster)	
Steering sensor	1	Steering angle sensor	N/A
V2X	5	802.11p	- 4 V2X module for 4 single camera (Front, Left/Right and Rear) - 1 V2X module for around view camera
HMI	1	Android	CAN, Automotive Ethernet
Controller	1	RCV controller	CAN, Automotive Ethernet
Communication	5	OBU	mmWave

KATECH provides the test vehicle, Arkana by Renault Samsung Motors, which is used for a remote-controlled vehicle via mmWAVE communication use case. The test vehicle equips various long and short-range sensors to detect obstacles around the test vehicle. Totally 8 HD cameras (4 sets of cameras for a real-time video stream of the front, left/right, and rear side video, and another 4 sets of cameras for a real-time video stream of around view) and 1 DGPS are also mounted in the test vehicle. There are 5 V2X modules (802.11p) for video data processing (LVDS to Ethernet) and it is connected to the mmWAVE OBU through network router. HMI (T2C) is connected to the network router for displaying all sensing, vehicle status data.

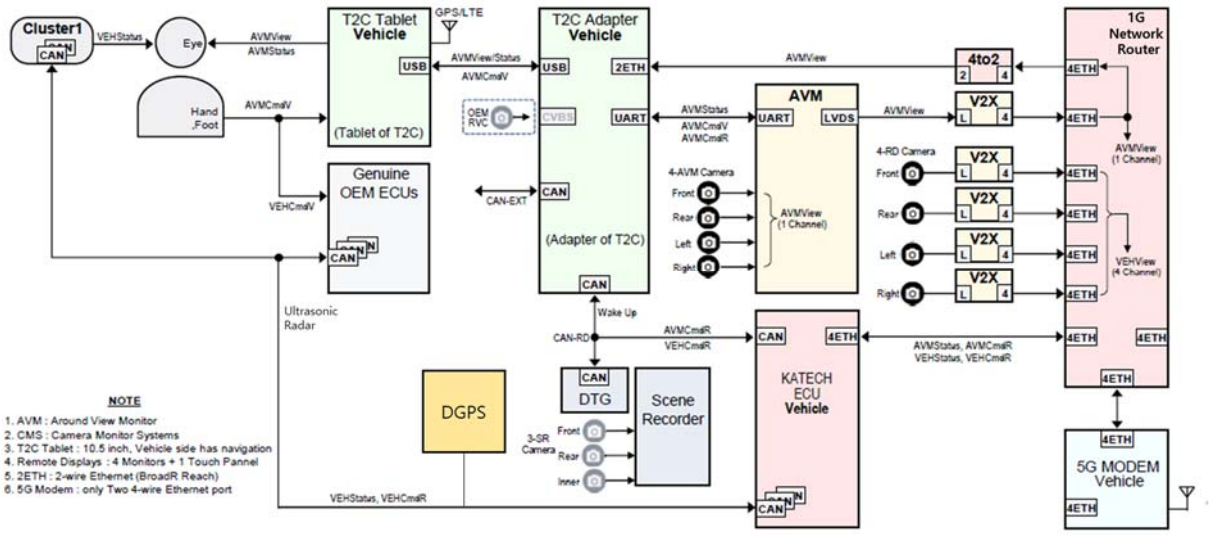

Figure 154: Overall architecture of sensor system of test vehicle

Figure 155: Sensor implementation of the RCV use case (Arkana / Renault Samsung Motors)

ETRI provides the test vehicle, SOLATI by Hyundai Motors, which is used for a tethering via mmWAVE communication use case. The test vehicle equips mmWAVE OBU and access point (AP, Netgear Nighthawk AX12) to provide internet connection to the passengers.

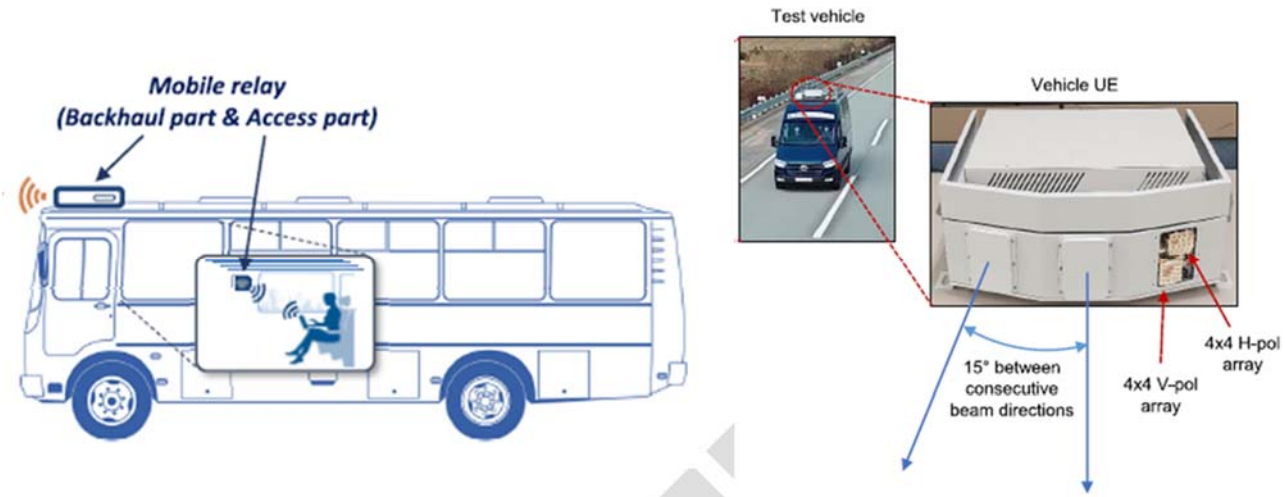

Figure 156: Sensor implementation of the tethering use case (SOLATI / Hyundai Motors)

5.6.2. Automated driving function development

To carry out the trials for the KR TS User Stories, the automated driving functions have been adapted. The vehicle fully supports not only lateral and longitudinal control but also transmission control to support remote driving. The test vehicle shares its each front, left and right, and rear video information and also its surrounding view video information with remote site based on mmWave communication. Lane recognition result that is detected by one of the front cameras is shared with remote server through mmWave communication link also. RADAR and ultrasonic sensors are mounted to support collision avoidance function. Front RADAR detects front obstacles such as vehicle, two-wheel bike, and pedestrian within 170m, 150m and 70m, respectively. Ultrasonic sensors are mounted at the front and rear bumpers and its obstacle detection range is maximum 120cm. Obstacle detection results are also transmitted to the remote server via mmWave communication.

CAN communication is mainly used to gather all sensor measurements (i.e. ultrasonic, radar), location data (DGPS) and vehicle status data (i.e. vehicle speed, steering angle, break), and these CAN data is converted to Ethernet packets by CAN to Ethernet converting module while V2X module converts video data (LVDS) to Ethernet packets. All sensor data made with an Ethernet packet is aggregated with video data by a network router and transmitted to remote server via mmWAVE on board unit. The figure below shows overall architecture of sensor system of test vehicle.

The following Figure 157 shows the software architecture for the vehicle:

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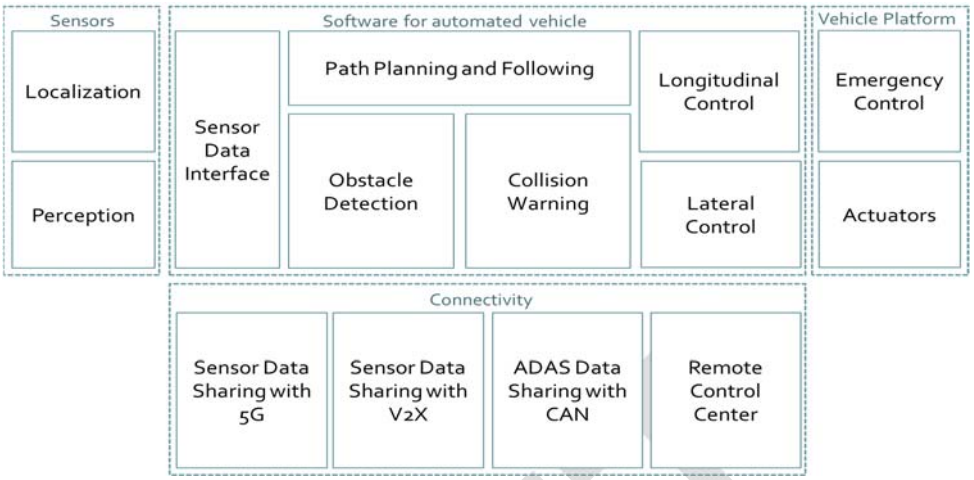

Figure 157: Automated driving functions of the KATECH vehicle

5.6.3. OBU integration

The mmWave -based OBU, also called User Equipment (UE), is installed in the test vehicle. The control plane (CP) and User plane (UP) protocols has been integrated across L1, L2, and L3 functions as depicted in Figure 155. L1/RF and L2/L3 functionalities of the vehicle UE are performed in separate modules. Similar to the gNodeB, the UE L2/L3 protocol stacks are implemented by software on a 2:2 GHz Intel XEON processor (D-2183IT). Since the same baseband board is shared by both the DU and vehicle UE, the UE L1 functionalities are implemented on the FPGA chips, similar to the DU. The main differences of the vehicle UE from the gNodeB-DU are the RF and antenna parts. The vehicle UE has a beam switching capability. To do so, the vehicle UE has three transmit and receive array antenna pairs, each of which consists of vertically and horizontally polarized components. The beam switching is controlled by L1 controller based on the RSRP measurements. The beam switching time is measured less than 1 us. In-vehicle UEs (e.g., smartphones) can access the network through a WiFi access point (AP) installed inside the vehicle, which is universally available and has a small coverage within a vehicle. the vehicle UE has a beam switching capability. To do so, the vehicle UE has three transmit and receive array antenna pairs, each of which consists of vertically and horizontally polarized components. The beam switching is controlled by L1 controller based on the RSRP measurements. The beam switching time is measured less than 1 us.

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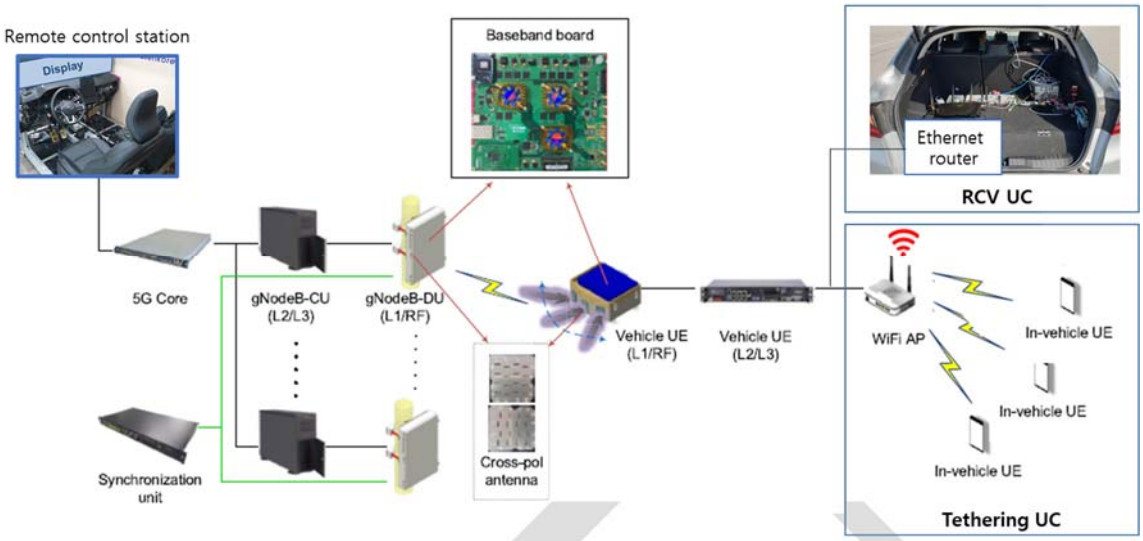

Figure 158: mmWAVE OBU integration

5.6.4. Early testing results

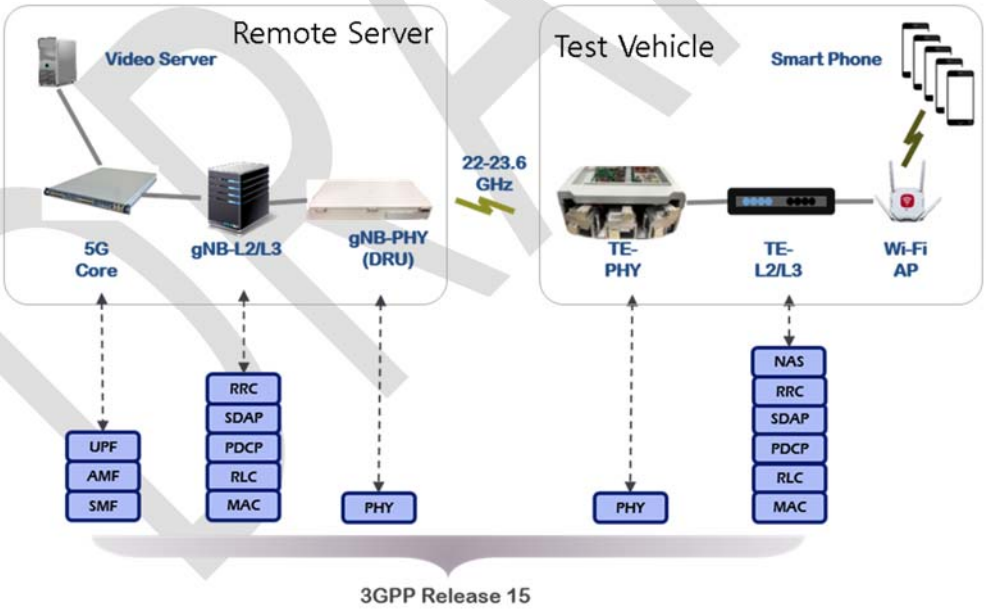

Figure 159: mmWAVE connectivity test

The early tests consist on simple connectivity tests between remote server and test vehicle via mmWAVE as shown in below Figure. Video server is connected to 5G core and share video file to test vehicle. User

connects to the video server with his/or her smart phone that is connected with AP in the test vehicle. User watching video, that is, downloading from video server in the remote site. Test results show that 3G bps @ downlink and 200Mbps @ uplink during the PHY to PHY test. The developed mmWave modem in the test vehicle was able to successfully connect to the mmWave network.

As a second phase of early trial, the implemented DUs are deployed on a highway test track for the tethering use case. The test track is located between Yeoju junction (JCT) and Gamgok interchange (IC) of Highway 45 of Korea, which was built parallel to the main highway. Out of total 7.7 km test track, a section of 2.7 km is actually used for the trial, where 5 DUs are deployed along the test track as illustrated in the figure below. The DUs are marked from ``1'' to ``5'' and the starting position of the vehicle is marked ``S''. The distance between the consecutive DUs is from 450 m to 750m. Each DU is mounted on a road side steel pole 15 m above the ground. Two cores of optical fibers are connected to each DU: One for the fronthaul connection to the CU and the other for the synchronized operation among the DUs.

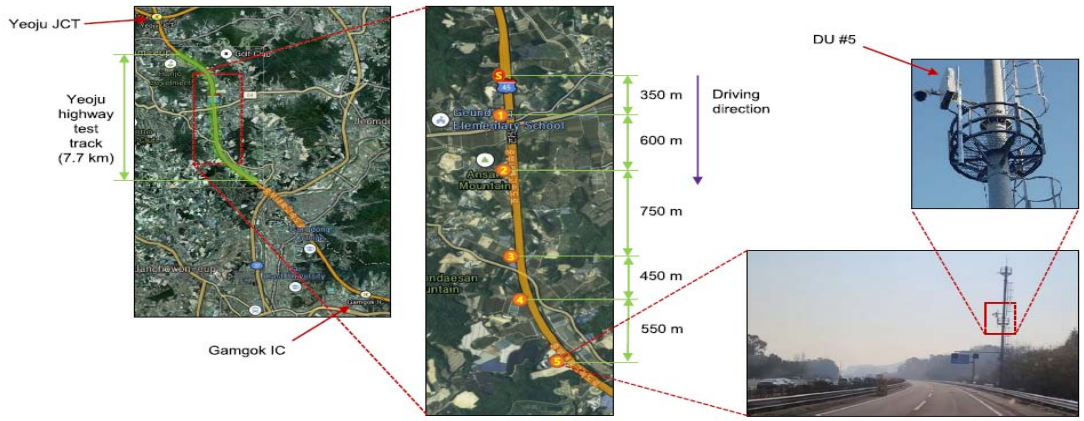

Figure 160: DU(RSU) deployment on a Yeoju highway test track

Figure below shows the test vehicle moving towards the DU. It can be observed that the DU is installed such that the beam of the DU sees the front face of the vehicle and the beam of the vehicle UE sees the driving direction of the vehicle. In addition, equipped with a beam switching capability, the vehicle UE can select the best beam among the three beams. The angular difference between the directions of the consecutive beams is 15 degrees, so that the vehicle UE can cover around 48 in total. For each beam direction, two 4 x 4 antenna arrays are placed and they are orthogonally polarized each other (i.e., horizontal polarization (H-pol) and vertical polarization (V-pol)), enabling 2 x 2 MIMO operation.

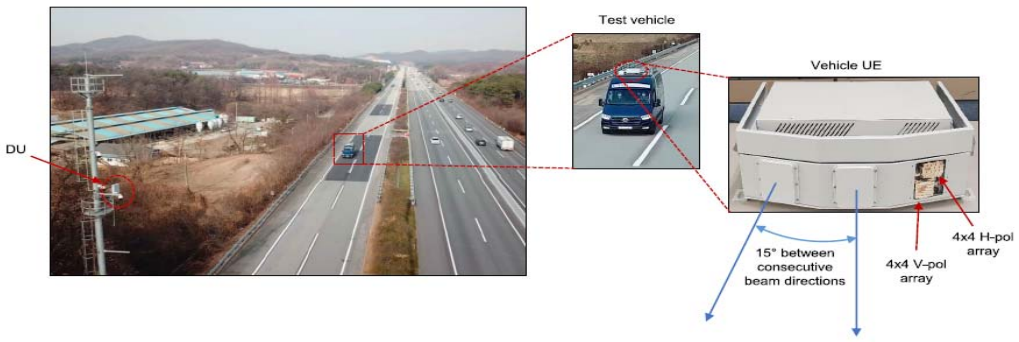

Figure 161: Early trail for tethering use case

The results of the field trial for tethering use case conducted on the highway test track as shown in figure below, which show the received SNR along with the traveled distance (a), the cumulative distribution function (CDF) of received SNR (b), and the CDF of data rate (c). Figure shows the received SNR as the test vehicle moves along the path from ``S'' (starting position) to ``5'' (last DU). The measured SNR ranges from 7 dB to 30 dB. It can be seen that the measured SNR is decreased with the distance between the DU and vehicle, obviously due to the increased path loss. In addition, the SNR is further decreased in the cell boundary regions, due to the interference from the neighboring DU. The CDF of the measured SNR is depicted in Figure below. Figure below (c) depicts the CDF of the measured data rate at the vehicle UE. Employing an adaptive modulation and coding (AMC) scheme along with the channel quality information (CQI) feedback, a set of modulation order (from QPSK to 64QAM) and code rate (from 0.245 to 0.889) is adaptively selected. As a result, it is seen that the measured data rate is closely related to the received SNR. It can also be observed that at least 1.15 Gbps of data rate is achievable for the 90% of the time during the test.

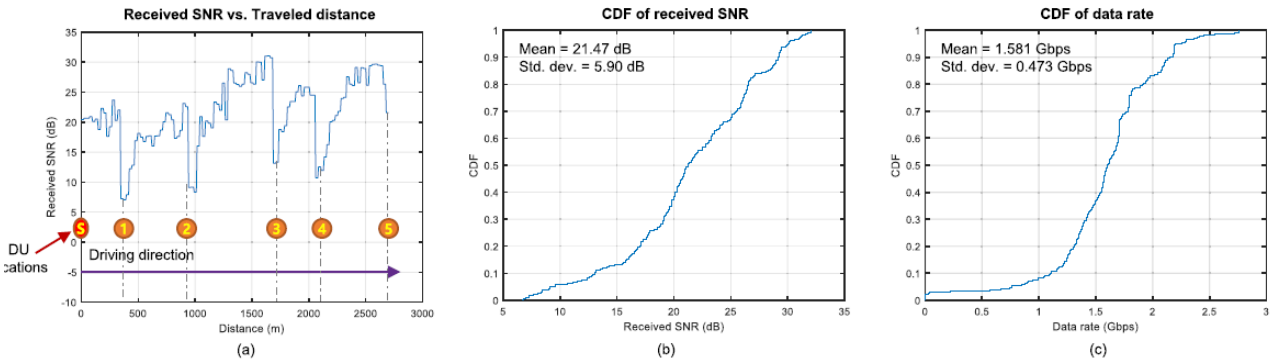

Figure 162: Field trial results: a) Received SNR vs. traveled distance; b) CDF of received SNR; c) CDF of data rate

As a third phase of early trial, the implemented remote controlled vehicle with mmWAVE system is deployed on a KATECH's closed test track for the remote controlled vehicle use case. The Level 4 automated vehicle, in this case a Renault Arkana, is equipped with a mmWAVE OBU and is used to test and validate remote-control use cases. There are a total of 8 cameras (front, left, right, rear, and 4 cameras for surround-

view monitoring) equipped for real-time video streaming to the remote server through mmWAVE communication found in the test vehicle. A remote control station was developed using real automotive parts from a Renault Arkana. The mmWAVE base station and core network are mounted in the moving base station vehicle, a Renault Master van with a remote control station. During the field trial, the key functionalities (real-time video streaming and control RCV via mmWAVE communication) are tested and validated.

Figure 163: Field trial of the remote controlled vehicle use case via mmWAVE communication in KATECH testing ground

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6. CONCLUSION

The present deliverable collects the detailed description of all the integrations, modifications and developments that have been carried out in vehicles and OBUs, as well as the initial testing process with the objective of ensuring the correct operation of all the systems.

The starting point that justifies all the activities outlined in this document is found in D2.4 (1), which in turn includes the needs of vehicles and OBUs required to carry out the different user stories defined in D2.1 (2). In addition, all the developments and integrations mentioned in this text will follow a testing process until the verification of the user stories is achieved, which will be detailed in D3.6 (4).

As a result of the activities described previously, the different partners in each Trial Site or Cross-border Corridor have obtained a series of vehicles and communication units adapted to 5G technologies, which will serve as a basis for exploring the possibilities of 5G applied to CCAM.

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