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

D6.5

Final report on the deployment options for 5G technologies for CAM

Dissemination level	Public (PU)
Work package	WP6: Deployment enablers
Deliverable number	D6.5
Version	V2.0
Submission date	06/06/2023 (post final review)
Due date	29/06/2022

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Control sheet

Version history			
Version	**Date**	**Modified by**	**Summary of changes**
V0.1	17/01/2022	Irene Saco	ToC draft, First document version, Executive Summary, Introduction
V0.2	03/06/2022	Irene Saco	First draft with partners inputs
V0.3	06/06/2022	Irene Saco	First draft to peer review
V0.4	15/06/2022	Irene Saco	Version for corrections and improvements after first peer review.
V0.5	18/06/2022	Irene Saco	Corrections and missing inputs complete. Version ready for second peer review
V1.0	27/06/2022	Irene Saco	Final version
V1.1	13/01/2023	Irene Saco	Executive Summary review, Technical Review comments completion.
V2.0	30/05/2023	Irene Saco	Final Version

Peer review		
	Reviewer name	**Date**
Reviewer 1	Janie Baños (DEKRA)	24/06/2022, 10/05/2023
Reviewer 2	Joaquim Ferreira (IT)	24/06/2022, 13/05/2023
Reviewer 3	Olga Segou (INTRASOFT)	04/05/2023
Reviewer 4	Coen Bresser (ERTICO)	31/05/2023
Quality review	Marie-Laure Watrinet (LIST)	24/06/2022, 22/05/2023

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ABBREVIATIONS

Abbreviation	Definition
5G NR	5G New Radio
ADAS	Advanced Driver Assistance System
APN	Access Point Name
CAM	Cooperative Awareness Message
CAM	Connected and Automated Mobility
CBC	Cross-Border Corridor
C-ITS	Cooperative Intelligent Transport System
CN	China
CPM	Collective Perception Message
CS	Considered Solutions
CV	Connected Vehicle
C-V2X	Cellular Vehicle to Everything
DE	Germany
DENM	Decentralized Environmental Notification Message
DNS	Domain Name System
E2E	Edge-to-edge
EDM	Edge Dynamic Map
ES	Spain
FI	Finland
FR	France
gNB	gNodeB
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GR	Greece
GRX	GPS Roaming exchange
GTP	Tunnelling Protocol

HO	Handover
HOM	Handover Margin
H-PLMN	Home Public Land Mobile Network
HR	Home Routed
HSS	Home Subscriber Server
ITS	Intelligent Transport System
KPI	Key Performance Indicator
KR	Korea
LBO	Local Breakout
LTE	Long-Term Evolution
MCM	Manoeuvre Coordination Message
MCS	Manoeuvre Coordination Service
MEC	Multi-access/Mobile Edge Computing
MME	Mobility Management Entity
mmWave	Millimetre Wave
MNO	Mobile Network Operator
MQTT	Message Queuing Telemetry Transport
MTU	Maximum Transfer Unit
NL	Netherlands
NSA	Non-Standalone Architecture
OBU	On Board Unit
PDU	Protocol Data Unit
PGW	Packet Gateway
PIC	Physical Cell ID Allocation
PLMN	Public Land Mobile Network
PT	Portugal
QoS	Quality of Service
RSI	Roadside Infrastructure

RSRP	Reference Signal Received Power
RSU	Roadside Unit
RTP	Real-time Transfer Protocol
RTT	Round Trip Time
SA	Standalone Architecture
SAE	Society of Automotive Engineers
SGW	Serving Gateway
SIM	Subscriber Identity Module
SMF	Session Management Function
TCP	Transmission Control Protocol
TR	Turkey
TS	Trial Site
TTT	Time-to-Trigger
UE	User Equipment
UP	User Plane
V2X	Vehicle to Everything
VM	Virtual Machine
VNF	Virtual Network Functions
V-PLMN	Visited Public Land Mobile Network
VPN	Virtual Private Network
VRU	Vulnerable Road User
WebRTC	Web Real-Time Communication
WP	Work Package
XBI	Cross-border Issue

EXECUTIVE SUMMARY

The main objective of this deliverable D6.5 “Final report on the deployment options for 5G technologies for CAM” is to present the main 5G deployment recommendations for cross-border Connected and Automated Mobility (CAM). These recommendations are the result of the analysis of technologies and technical evaluation results of 5G tests and trials conducted in two cross-border corridors (CBC) (Spain-Portugal and Greece-Turkey) and six local test sites (TS) in Europe (Germany, Finland, France and the Netherlands) and Asia (China and Korea). D6.5 revisits the set of initial challenges, recommendations and deployment options elaborated on D6.1 “Plan and preliminary report on the deployment options for 5G technologies for CAM” to provide the main 5G for CAM guidelines based on deployment, verification, validation and evaluation tests carried out in 5G-MOBIX.

The consolidated list of recommendations is elaborated on the analysis of problems arised during the deployment of 5G for CAM and directly explored in the different tests, trials and experiments in cross-border environments, which can be categorised at two levels:

Micro-level recommendations, based on the expertise acquired across the Project on the following fields:

- **Deployment →** The current state-of-the-art of 5G deployments is supported by: MEC infrastructure to decrease the latency; direct interconnections between neighbour networks to shorten handover times; and precise design of antenna as well as, MEC (Mobile Edge Computing) and core locations to optimise coverage and efficiency.
- **Data →** The coexistence of the different tools to measure the specific flows in the test cases is harmonized by means of the common data format, that also serves as the basis to obtain the KPIs for the technical analysis.
- **Application and interoperability →** Applications are functional in the 5G environment but the time to change the sessions appears now, in comparison, too long. Interoperability is achieved but with ad-hoc solutions.
- **Cybersecurity →** The protection of the 5G network depends on the end points of the communication and the CAM applications deployed, for instance: MQTT servers are secured with a TLS layer, the file sharing with SFTP (secure file transfer protocol) and the services in Core and MEC with VPN (virtual point network).
- **Automotive industry and CAM →** Common standards and protocols are already established to ensure smooth and efficient communication between vehicles and road infrastructure and to achieve effective, continuous and seamless session change management. Collaboration between automotive manufacturers, service providers and regulatory bodies ensure compatibility and successful implementation of CAM systems in the automotive industry.

- **Road →** To assure availability (coverage) and efficiency of on-road communications, antenna locations, as well as the MEC service access points and cores, should be precisely designed.

The following **recommendations are proposed as solutions for the cross-border environment.** It is based on the 11 key technical challenges (X-Border Issues, XBI), and their corresponding considered solutions, identified by the project to guarantee **service continuity in a cross-border context**:

Mobile Network Operators (MNOs)

- S1 handover with S10 interface and HR is the baseline configuration options in 5G Non-Standalone (NSA) Option 3x because they provide handover times compatible with the performance of most of the CAM functions. LBO roaming reduces latency when driving in the neighbour PLMN but the need to set up a new data session after the handover increases the mobility interruption times being critical for many CAM services.
- In environments with few networks, it is advised to establish Direct Interconnection links. However, in more complex multi-PLMN or pan-European mobility environments, scalability and complexity issues may arise, and a careful assessment should be conducted from both a technological and economic perspective.
- The location of the server (cloud or edge computing) has a direct impact on the latency.
- Studies on mmWave applicability show its viability for high capacity in data delivery.
- Satellite communication is presented as an alternative for low coverage areas but further studies are still needed to increase the throughput and reliability.

Original Equipment Manufacturers (OEMs) / CAM Service Providers

- For services that are expected to operate on a small scale, involving only 2-3 PLMNs, it is recommended to use multi-modem / multi-SIM User Equipment (UE). This recommendation applies in the short to medium term until SSC mode 3 becomes available, which depends on the vendor's specific roadmap. To better understand the market demand and the delivery of SSC mode 3 by vendors, it is necessary to carefully balance the costs of this solution against the amortization period.
- It is necessary to make improvements and optimizations in widely used application-enabling protocols such as MQTT and WebRTC. These improvements should be taken into serious consideration during the design and development of services.
- It is strongly recommended to conduct extensive testing of terminal devices to ensure operational stability.
- Coordination between Service Providers/OEMs and MNOs is recommended, particularly regarding service discovery aspects in the context of LBO configuration. Local DNS/service discovery should be available and always aligned with the underlying routing configuration, directing to the closest server. Additionally, considering DNS caching on the device can help avoid service discovery latencies.

The recommendations initially proposed in D6.1 have been transferred to the technical work packages where most of them have been validated in line also with the proposed XBIs. The challenges addressed focus on ensuring service continuity in the context of 5G for CAM and include minimising signal and coverage losses, optimizing network configurations and infrastructure support, and fostering collaboration and cooperation between industry stakeholders and authorities. Overall, ensuring 5G service continuity in a cross-border context requires an approach considering technical, regulatory, and operational aspects. During the trials conducted in the project, most of the recommendations presented in this document have been implemented and, in this context, the deployed 5G networks have been able to provide uninterrupted connectivity for enabling cross-border mobility to customers in most cases [1].

1. INTRODUCTION

1.1. 5G-MOBIX concept and approach

5G-MOBIX aims to showcase the added value of 5G technology for advanced Connected and Automated Mobility (CAM) use cases and validate the technology's viability to bring automated driving to the next level of vehicle automation (SAE L4 and above). To this end, 5G-MOBIX has demonstrated the potential of different 5G features on real European roads and highways, creating and using sustainable business models to develop 5G corridors. 5G-MOBIX has also utilized and upgraded existing key assets (infrastructure, vehicles, components) allowing 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 conducted a series of CAM trials along cross-borders (x-border) and trial sites using 5G technological innovations to qualify the 5G infrastructure and evaluate its benefits in the CAM context. The Project has also defined deployment scenarios and identified and responded to standardisation and spectrum gaps.

Firstly, 5G-MOBIX has defined critical scenarios requiring the advanced connectivity provided by 5G, and its associated features, to enable selected advanced CAM use cases. The matching of these advanced CAM use cases and the expected benefits of 5G were tested during trials on 5G corridors in different EU countries as well as in Turkey, China, and Korea.

The trials also allowed 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 identified new business opportunities for the 5G enabled CAM and proposed recommendations and options for its deployment. These findings have been presented in deliverable D6.1, and in the *5G for CAM- A Deployment Metastudy* (this document can be consulted on the project's website: (https://www.5g-mobix.com/).

The overview of the costs of 5G for CAM technology found in literature references was validated by 5G-MOBIX project partners with the Trial Sites and Cross-Border Corridors support, considering the specific characteristics of each of them. Therefore, this final analysis presents the 5G technology deployment options for the CAM to meet the objectives of task T6.1.

1.2. Purpose and structure of the deliverable

5G-MOBIX dedicates Work Package 6 "Deployment Enablers" to drawing input from the project trials and identifying options for V2X connectivity deployment. The main objective of WP6 is to evaluate and exploit the results of the trials. The options may include co-existence or hybridisation possibilities with other technologies. In this sense, WP6 contributes to developing the work items related to the 5G-MOBIX use cases and 5G infrastructures, but also beyond them.

In particular, the purpose of this document is to evaluate the current state of 5G technologies concerning to CAM and evaluate its evolution potential. The specific goals of task T6.1 and D6.5 are to:

- Focus on the application of 5G telecommunication infrastructures on the transport sector.
- Contribute to creating of a multiplier effect on project results by implementing a two-sided recommendation and deployment strategy called 'from local-to-project-to-global'.
- Provide recommendations and deployment options for post-project replication partners as crystallisation points for taking up project results (D6.1 & D6.5).

To achieve these goals, work has been carried out in task T6.1, based on the extensive analysis of 5G technology for CAM previously presented in D6.1, and taking that analysis to the real test environments defined in the project in each CBC and TS. A new update takes places with this deliverable D6.5, allowing the analysis to assess potential, both in terms of application and evolution.

This document focuses on the progress made on what was previously presented in D6.1 based on field experience and the current organisation of objectives, which are based on the identification, description and solutions to a series of challenges called XBI (x-border issues). It takes up the point of view of applying a two-way recommendation and deployment strategy called "***from local to project to global*** ". This deliverable complements and updates D6.1 but does not replace it. Therefore, D6.1 should be taken as the main reference document for a complete understanding of D6.5.

This document is organised as follows:

- **Section 1** (current chapter) introduces the project and the scope of this work.
- **Section 2** provides an overview of the challenges that technology 5G for CAM technology is facing at the industrial level and the lessons learned. It focuses on recommendations and deployment options to simplify the deployment and management of 5G for CAM in cross-border scenarios.
- **Section 3** synthesises the conclusions of D6.5.
- **Section 4** collects the bibliographical references used throughout this document.
- **Section 5** contains the Annexes to this deliverable.
    - **Annex 1:** Deployment Study.

1.3. Intended audience

The current document is publicly disseminated and is available as a free download on the 5G-MOBIX website[1]. It is meant primarily as a handbook that introduces 5G concepts to CAM stakeholders and discusses the potential evolution of this technology in terms of providing CAM functionalities. Foreseen issues and barriers to the deployment of 5G are discussed to form a common basis of understanding on

[1] 5G-MOBIX website: https://www.5g-mobix.com/ [Accessed May 2021]

which stakeholders can initiate discussions on the future of 5G for CAM. Thus, this document aims to serve not just as an internal guideline and reference for all 5G-MOBIX beneficiaries, especially the Trial Site (TS) and the UCC/US leaders but also, for the larger communities of 5G and CAM development and testing.

Interested readers may also refer to:

- *D6.1 - Plan and preliminary report on the deployment options for 5G technologies for CAM.*
- *D6.2 - Plan and Preliminary Report on the business models for cross-border 5G deployment enabling CAM.*
- *D6.3 - Plan and Preliminary Report on the standardisation and spectrum allocation needs.*
- *D6.4 - Plan and Preliminary Report on EU Policies and regulations recommendations.*
- *D6.6 - Final report on the business models for cross border 5G deployment enabling CAM.*

Other interesting reference documents include:

- *D3.7 - Final report on development, integration and roll-out.*
- *D4.3 - Report on the corridor and trial site test activities.*
- *D5.2 - Report on technical evaluation.*
- *D5.3 - Report on impact assessment and cost-benefit analysis.*
- *5G for CAM: A Deployment Metastudy. A synthesis of three Pan-European studies on 5G deployment for connected, automated mobility in border regions.*

These documents are also available as a free download on the 5G-MOBIX website (https://www.5g-mobix.com/).

2. 5G FOR CAM CHALLENGES AND LESSONS LEARNED

2.1. General challenges and lessons learned for 5G for CAM

This section reviews the main challenges for the deployment of 5G technology for CAM applications that were presented in D6.1 (Figure 4) by compiling the main solutions adopted in WP3 (Development, integration and rollout), WP4 (Trials) and WP5 (Evaluation), WP3 ran the CAM-agnostic tests, to validate the network deployment (and the verification tests, to check step-by-step the CAM implementations), WP4 executed the CAM-specific tests and WP5 obtained and analysed the results of the cross-border issues related tests.

2.1.1. Deployment

The deployment of 5G network-oriented CAM applications involves the close liaison and cooperation of different stakeholders to satisfy the complete chain of responsibilities from deploying of the 5G network to the design and execution of the CAM applications, as depicted in (Figure 5). This is especially challenging when: 1) the communication technology is novel, since this process implies going beyond the state of the art; 2) the vendors are still working with primary versions of the new devices or 3) the 3GPP standardisation is an ongoing process.

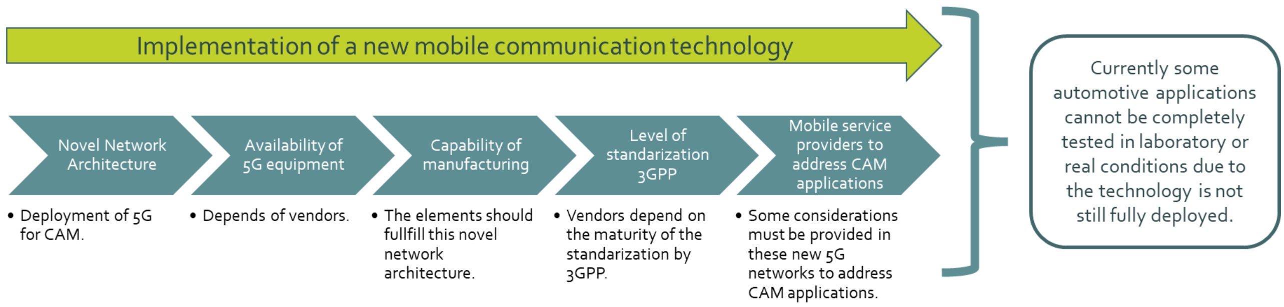

Figure 1: New mobile communication deployment implications

The whole Consortium, in the framework of WP3, faced these issues with fulfilling the Project objectives. Below, are the main lessons learned during the deployment:

Network lessons learned:

- Core and RAN equipment did not provide advanced 5G features, especially in SA, which caused both results below the expectations and limitations in the test design.
- Network slicing is already functional but it is not mature to work in stressed networks. MEC deployment considerably decreased the latency, especially when positioned close to the testing environments. In cross-border areas, HR latencies depend on the distance to the H-PLMN.

- Satellite communications provided a limited level of service, only valid for applications not requiring low latencies.

- Measurement equipment was employed to test the network performance and calibrate the coverage provided by the antennas and gNBs. Low radio power areas and radio signal losses were identified and corrected by re-orienting or re-positioning the antennas. Also, the undesired ping-pong effect in cross-border areas was addressed by fine-tuning the RAN parameters of the involved MNOs (the HO thresholds broadcasted in the selected areas).

- CBCs directly interconnected their networks through the S10 interface achieving low handover times in home routing guaranteeing service continuity for the CAM applications. With direct interconnection, the round-trip time (RTT) is significantly improved. The communication between the OBU and the edge server, via the H-PLMN is sufficient to adequately perform all intended User Stories functions.

- During trials, with a MEC-CORE configuration, it is very important to take into account the physical position of the MEC centre and the central cores before setting up one network configuration or another (e.g., of HR and LBO). It was shown that if the MEC centre is too far away from the manoeuvring area, it negatively impacts the performance, leading to higher latencies.

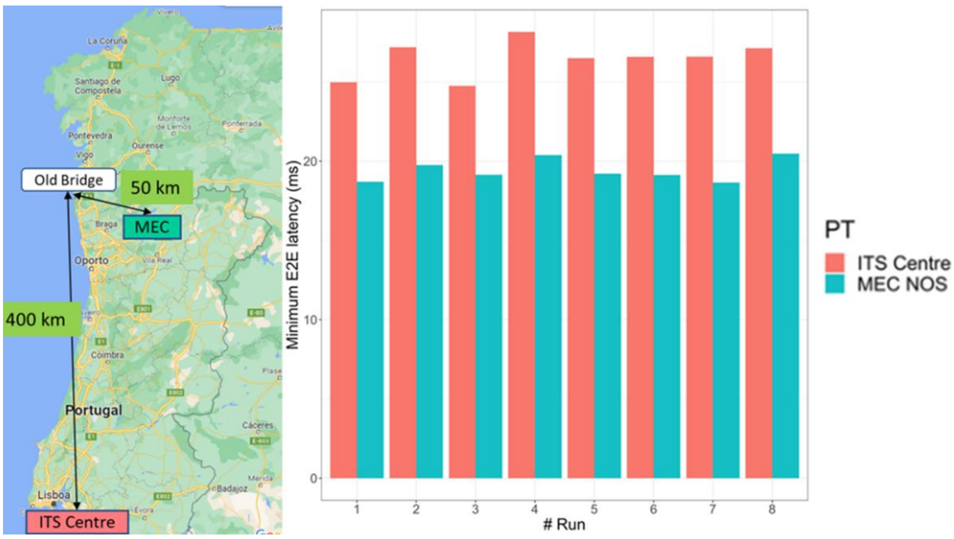

Figure 2: The minimum latency value is lower when testing against MEC (green) than against the ITS Centre (red), due to its closer distance to the test field.

- In border areas, the most logical configuration is HR. At the same time, LBO could be used in areas far from the border, applying there a latency reduction since the equipment of the country where the user is located will be used. Nevertheless, it is very important to consider the physical location of the MEC centre before establishing one configuration or the other, since if it is too far from the area where the manoeuvres are to be carried out, it has a negative impact, preventing the MEC to fulfil the expected throughput and latency requirements of 5G networks.

Situational lessons learned:

The test environment affected the repeatability of results, meaning that the control of the following factors may impact the power of the communications and, therefore, the results. Analysing the environment and correct location of 5G antennas and sites helped select the most suitable automotive antennas and modems to ensure better coverage and communications.

- Antenna coverage was reduced by metallic elements acting as signal blockers. This effect was reduced during the field tests in some cases by installing a small cell. In other cases, the short term solution was covering the panels with a thick plastic sheet. This sheet reduced the ability of the metal panel to adequately reflect radio signals. Anyway, both solutions are not scalable on large-scale deployments but have corroborated the impact of antenna placement and other non-technological elements that can affect coverage.

- The foliage level across the seasons, mountains, or buildings was demonstrated to interfere with the line of sight of the antennas.

- The number of users consuming 5G resources caused worse results because of the effects of network sharing.

- Rain and fog also affected 5G communications degrading its performance.

Figure 3: The metal structure of the Old Bridge ES-PT acts as a signal attenuator. This effect was mitigated with the installation of a small cell.

Figure 4: The metal information road panel in A28 ES-PT causes radio signal blocking. This effect was mitigated by covering it with a thick plastic sheet.

Other lessons learned:

- Dividing the mobile network into regions and keeping traffic in one region would enable a dedicated direct data network solution at cross-border sites. This requires the creation of regional interconnection agreements between operators.
- The combined use of 5GNR and satellite access is an alternative that could deliver high QoS for resilience and redundancy in the communication link, for example, through a hybrid platform that utilises both 5G-NR and Low Earth Orbit Satellite Connectivity.
- The limited availability of fibre networks in many locations, or location where fibre backhaul deployment cannot be considered cost-effective, could be addressed by wireless backhaul technologies instead of fibre backhaul. A portfolio of wireless technologies, including point-to-multipoint communications, 5G mmWave and satellite, should also be considered as technology maturity progresses.
- For any deployment, it is recommended to carry out field tests to ensure that the network delivers the desired performance. During the project, these tests were used to detect and correct problems and to improve network optimisation and settings.
- During the 5G-MOBIX deployment decision support tools capable of performing basic measurements and simulations of road traffic and networks were used. This type of technology is useful for accelerating critical research and development to support 5G-Advanced use cases for example.

2.1.2. Data

The great amount and heterogeneity of data was managed at both local and central levels to respect both the freedom of choice of tools from CBC/TS side and the harmonisation of results at the project level.

At the local level:

- Many different tools were employed to characterise the networks and collect data. The coherence of results validated their suitability for this new communication technology.
- The precise synchronisation of the different points of control and observation (including user OBUs/RSUs, MECs, ITS Centres, etc.) was the key to obtaining reliable results from the analysed data flows.
- Analysis at the local level provided consistent results that validated the different approaches.

At the central level:

- The harmonisation efforts were addressed through the aggregated measurements required to obtain the technical KPIs. This led to the design of a common data format valid for the different network designs and test cases and crucial for interoperability and efficient communication between different systems and tools. It includes a set of commonly agreed specifications and guidelines between the partners that define how the data should be structured, organised and represented.
- The logs in the common data format had to pass a sanity check to assure conformance with the data format and physical coherence of the measurements.
- A common tool (Data Builder) was designed and developed to ease the upload process of the files in the common data format and complete the test case description.
- The centralised test server included a web application to look up the common data format files.
- The centralised database provided agile access to the data and enabled data analysis and cross-comparisons across CBC/TS.
- Data are supplied to the RSU at discrete times/timestamps. To minimise the receipt of data with the same timestamp but with conflicting contents (both being valid at the time of data acquisition), prioritisation systems based on the timestamp can be applied so that the most recent data receives a higher priority, filtering systems can be incorporated to take into account the reliability of the data source, fostering the establishment of a data validation process.

2.1.3. Application and interoperability

3GPP Release 15 [2] introduced 5G New Radio (5G NR), enabling higher data rates and lower latencies for V2N network communications. In addition, Release 16 introduced some core functions related to massive Machine-to-Machine and some aspects of communications with Ultra Reliable Low Latency Communications (URLLC). All these enhancements are expected to result in greatly increased bandwidth, and even lower latency, and usage of 5G NR to support V2V and V2I, often referred to as 5G-V2X.

5G car connectivity enables vehicles to connect to each other, to the infrastructure, to network services, and to other road users such as cyclists and pedestrians. That means roads can be safer, faster, and more energy efficient. In-vehicle infotainment will make journeys more pleasant too.

Service providers work with automotive companies and other ecosystem partners to enable new connected vehicle-to-everything (5G C-V2X) applications, including:

- Real-time situational awareness and high-definition maps.
- Cooperative manoeuvring of autonomous vehicles.
- Software updates.
- High-definition sensor sharing.
- Tele-operated driving.

During the project, several Application VNFs were deployed in several operators' networks that interacted by using the MEC connectivity. These applications support different flows of information grouped into four different categories: telemetry, remote control commands, video uplink flows and video downlink flows. These different flows had different QoS requirements for different CAM Use Cases and could be mapped to different 5QIs (5G QoS Identifier).

To address the disconnection times when crossing an area between more than one PLMN, different options are proposed as a solution.

- Through user space applications running on the device (or even on the SIM), the device can perform a full network search before crossing the border and it can be instructed to connect to a new network before the connection degrades.
- Otherwise, a multi-modem approach can be adopted to connect to the new network first before breaking up with the old one. From the network operators' side, in coordination with modem manufacturers, it is possible to agree on the most suitable network quality parameters for in-vehicle devices.

* In case the handover needs to take place in a predefined small area in the border for manoeuvre purposes, the close collaboration of network and OBU's provider sides is essential to precise the threshold values for the RSRP to adjust them to the antenna gain of home and visiting PLMNs.

This adjustment of network parameters also allows, during the trials, to avoid undesirable handovers and to reduce the ping-pong effect that has been identified during border trials, where the connection was handed over from one cell to another but was quickly returned to the original cell. This effect decreases throughput and increases packet loss and latency. To decrease the ping-pong effect, Times to trigger (TTT) were defined for the execution of the use cases where if the connection condition is met and during the TTT, the drop condition is not met then the network handover event is triggered. Proper selection of the TTT ensures smooth handovers in a synchronised manner, too large a value will delay the handover and service may be lost.

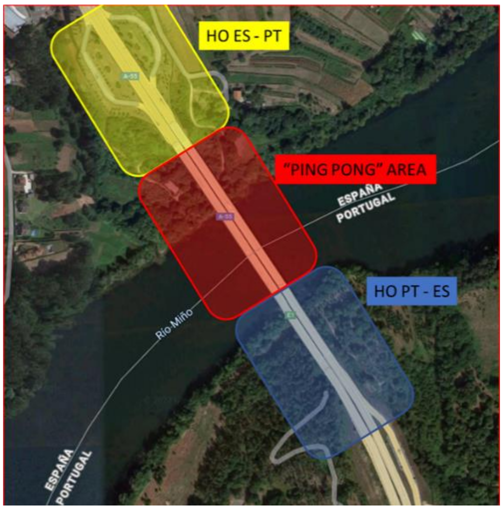

Figure 5: HO in ES-PT CBC location

The 5G-MOBIX project has developed methodologies and platforms to test and assess critical usage combinations of 5G networks in worst-case scenarios. This approach addressed different physical locations and architectures of data centres and highlighted the impact of network core and VM performance on data latency and bitrate levels. The project also developed a tool to simulate multiple OBUs and assess the impact of background data traffic on the 5G radio interface network compared to a dedicated/empty 5G radio network scenario. The observed data latency and bitrate levels, and their corresponding variations, are dependent on the network core and VM performances and the radio capabilities.

Regarding session initiation protocols, the application layer protocols used in several services, i.e., WebRTC, and MQTT, caused considerable service interruption when it was necessary to re-establish the session, after a mobility event.
During the 5G-MOBIX project, there were connection issues due to interoperability limitations related to the use of 5G chipsets from different vendors that had to be overcome. Some limitations were observed

with some parameters when working with different regional configurations of the MNOs that sometimes prevented to enable consistent and reliable connectivity.

2.1.4. Cybersecurity

As 5G network deployments increase, the associated cybersecurity challenges also increase. Some of the main cybersecurity challenges in 5G networks were identified, based on ENISA's report [3]. During the 5G-MOBIX project, some related countermeasures were defined that can be translated to the 5G CAM environment as recommendations. Some of the actions carried out in the project that can be translated into recommendations focused on the protection of the network are:

UCC#1: Advanced Driving

A secured MQTT service protects the communication between vehicles and infrastructure. This service is installed in each OBU unit as an MQTT client with a TLS layer. This implementation is also available on the MQTT server side, with a TLS layer.

The OBU creates a unique private key which is sent to the registration server. After that, the OBU requests a JWT (JSON Web Token) to the server and it returns the JWT and the Geoserver address where the OBU must establish the communication. Finally, the OBU subscribes to the topics of the specified Geoserver.

In this way, communication between all actors is secured and they can exchange ITS messages.

Lessons learnt & recommendations:

- This technique worked without any issues, and, although injects certain overhead, the service worked smoothly.

UCC#3: Extended Sensors at Cross-Border Scenario

The files exchanged between remote actors are secured with the Secure File Transfer Protocol (SFTP). This protocol allows the transfer of encrypted data between two hosts using Secure Shell (SSH), with the help of a user and a password to upload and download the files.

Lessons learnt & recommendations:

- This method of sharing files was proven to be secure but inefficient. The transmission of complete files every time wastes time and bandwidth that can be optimised using incremental synchronisation tools. These tools simplify the process of synchronizing changes made in a dataset, database, or file system by identifying and transferring only those data elements that have changed or are new since the last synchronisation.

UCC#4: Remote Driving

To carry out this UCC, a VPN was implemented using OpenVPN, therefore, the exchange of information between the control centre and the Shuttle is encrypted end-to-end. Provisioning of network certificates is done manually during the configuration phase.

Lessons learnt & recommendations:

- This solution has proved to be very successful. It was so good that it was decided to extend the VPN to the entire CAM network.

UCC#5: Vehicle Quality of Service Support at Cross-Border Scenario

In this case, the video streaming access and application are protected with a user/password registration.

Lessons learnt & recommendations:

- A username/password scheme protects the authorisation property but does not protect against attacks on confidentiality and integrity. Both can be mitigated by expanding the VPN implemented for UCC#4.

Overall system

Securing communication between different parties in cross-border areas relies on the respective national MNOs.

Lessons learnt & recommendations:

- Since the communication was between two national MNO networks in a cross-border environment with two different addressing schemes, many addressing issues and security concerns showed up during the deployment. Expanding the VPN implemented for UCC#4 among the other actors appeared as a successful solution.

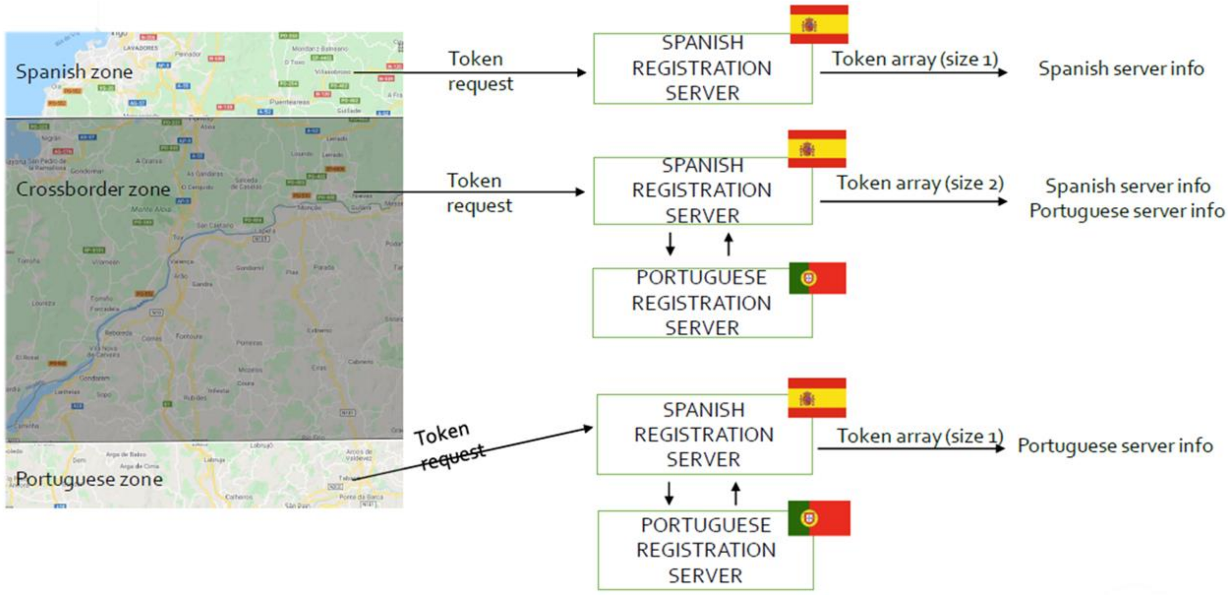

Figure 6: Simplified scheme for the definition of border areas made in the CBC ES-PT

At the technical level, it is also proposed to perform a prior threat analysis, prioritise critical threats and deploy appropriate countermeasures. Tools like the Honeypots used by INTRA can act as a sacrificial infrastructure for gathering threat intelligence (Figure 7).

Figure 7: Detailed results from the INTRA Honeypot indicating an attempt to utilise NTP for a DDoS Amplification attack.

2.1.5. Automotive industry and CAM

The automotive industry must align its developments with safe, secure, reliable and highly pervasive driving functions. To have safe, secure, reliable and highly pervasive driving functions, it is necessary for the automotive industry to align on their development. The efforts of 5GMOBIX were focused on:

- Service continuity was achieved in HR roaming with radio handover times of a few hundred milliseconds, a threshold acceptable for most of the CAM functions. Still, the current state of the art of LBO only allowed handover times in the order of seconds, disabling the performance of CAM functions.

- More efforts must be made on the application side to make agile the connection to sessions on the Cloud that considerably increases the interruption times.

- 5G positioning was enhanced by taking advantage of the properties of 5G mmWave signals, making possible the safe driving of autonomous vehicles and the remote control.

OBU/RSU lessons learned:

- Availability and support from 5G chipset vendors was limited, and 5G-MOBIX found compatibility issues and the need for particular regional settings. In the future, more stable versions of 5G chipsets will boost their performance and reliability.
- OBUs/RSUs were prepared to work with the new 5G chipsets, requiring hardware integrations and the provision of new drivers.

- The maximum capacities that can be obtained from the deployed network are evaluated by means of agnostic tests using experimental devices. Based on these expected measurements, the communication capabilities of the OBUs/RSUs were adjusted and improved. Therefore, in both cases, low latencies, high throughput and extreme reliability were obtained.

- Multi-modem SIM OBUs with link aggregation showed better performance in terms of latency, throughput, and reliability over both single-modem OBUs and multi-modem OBUs with link selection.

- In the future, it is expected that mechanisms and configurations to minimise disconnection times across borders will be fully implemented from the network, thus avoiding that in-vehicle network devices may conflict with network-based handovers.

- Verify the compatibility of 5G OBUs and other vehicular connectivity devices in multi-PLMN environments, especially for relatively immature SA-mode devices.

- For V2X deployments in networks with multiple PLMNs, a reconfiguration in one PLMN may affect other PLMNs as a side effect. Having nodes configured with multiple PLMNs using a specific configuration in some radio frequency bands should be independent of the configuration in other bands.

- It is important to ensure that telecom service providers establish adequate interoperability to ensure proper connection and operation of 5G OBUs in their networks.

Other lessons learned:

In both border crossing trials, it was shown that 5G - NSA LBO could not be used for 5G-CAM applications with strict requirements in terms of service interruption, since service continuity was interrupted for more than 5 seconds. The automotive industry shall consider such network bottlenecks when designing their applications and ensure they are more resilient to network service discontinuity.

Without precise positioning features in autonomous vehicles, it is impossible to follow defined paths, lanes and arrange vehicle speeds. Buildings, bad weather, etc., can affect conventional positioning techniques. For a seamless positioning feature, 5G positioning capabilities should be considered (both GPS correction using GPS and 5G positioning).

2.1.6. Road

For road operators, it is important to know all that is happening on their roads, and the sooner they receive this information, the better management decisions they can make. Relevant information includes meteorological conditions, traffic data, traffic incidents, etc. Traditionally, this information is obtained from meteorological stations, CCTVs and phone calls of users, but since these methods cannot cover all road stretches, there will always be blind spots. With 5G communications, during trials, connected vehicles served as a real-time information provider of the road and the road environment. The vehicle can provide an important source of information that is highly up-to-date and accurate.

Another motivation is that, with 5G communication, it is possible to inform all users in a given section of the highway about any incident that may take place. With 5G, it is possible to have warnings with very low reaction times (latencies), both in VMP (Variable Message Panel) and by sending the information to the connected vehicle (V2x) at any point on the motorway.

The main challenges, for road operators to overcome are to:

- **Improve road safety** on the road network.
- **Optimise traffic flow** on arterial and motorway networks.
- **Manage incidents**, reduce delays, adverse effects of incidents and congestion, weather, road works, special events, emergencies, and disaster situations.

- **Effectively manage maintenance and construction work** to minimise its impact on safety and congestion.
- Provide traveler with **timely and accurate information**.
- **Harmonisation of spectrum allocation** between regions and countries by reducing timeframes for spectrum use agreements.
- **Collaborate on regulation** to expedite the deployment of 5G on roads.
- While 5G offers a significant increase in speed and bandwidth, its more limited reach will require more infrastructure so **more equipment is needed for greater coverage** in certain use cases.
- Road managers must also be responsible for **road maintenance**, so that poor road conditions do not hamper CAM functions.
- **Up-to-date and adequate equipment** in line with the requirements of today's communications technologies is essential for the further development of 5G deployments.
- **It is imperative to create platforms to exchange traffic** information with a good processing system for filtering and triggering events **to reduce implementation costs and ensure data privacy and reliability.**
- **Collaboration between different entities** to facilitate deployments and testing in cross-border environments is crucial. During the 5G-MOBIX trials, border scenarios of different complexity were encountered. Hard-frontier scenarios, where the bureaucracy considerably limited testing, soft-frontier scenarios, where the bureaucracy was easier but where the scenario conditions required mobilising many resources.

2.2. Cross Border Challenges

The work of 5G-MOBIX aimed to identifying the key challenges in deploying seamless connectivity to CAM enabled vehicles when crossing national borders and hence performing an inter-PLMN Handover (HO), resulting in roaming to the visited PLMN. 5G-MOBIX also aimed at, and to testing and evaluating the effectiveness of different features, configurations and solutions and addressing the respective challenges, and also driving the discussion regarding the deployment options that MNOs and OEMs would tend to focus on, based on the applicability and results delivered by each of the 5G-MOBIX solutions.

To better understand the lessons learned during deployment, it is crucial to first explain the working methodology implemented in the 5G-MOBIX project, and the resulting ***Cross-Border Issues (XBI)*** and ***Considered Solutions (CS)***, around which the evaluation framework was built. 5G-MOBIX experts have identified the key challenges XBIs that contribute to service interruption and/or performance degradation (in terms of latency, reliability, throughput, etc.) when a CAM-enabled vehicle is crossing national borders and consequently changing its serving PLMN. During this process, the vehicle is performing an inter-PLMN Handover, leaving its home network (PLMN) and ending up roaming in the visiting PLMN. The identification, performance degradation measurement and impact analysis of each of these XBIs, has been the key focus of all the 5G-MOBIX Cross-Border Corridors (CBCs) and national Trial Sites (TSs).

The most promising 5G features, technologies and configurations/settings that could mitigate or even completely counteract the effects of each XBIs, were identified by the 5G-MOBIX experts and listed under the common name Considered Solutions (CSs). Each CS constitutes a potential solution that could be implemented on the network, vehicle/OBU or application level and has a significant chance of improving the experienced connectivity performance when performing an inter-PLMN Handover. Specific XBI-CS pairs were defined and trialled at each of the CBCs/TSs to provide insights on i) the impact of a certain XBI on the experienced performance of each of the selected CAM use cases, ii) the degree to which each of the progressed CSs mitigate the impact of the respective XBI and delivers the best possible performance during border-crossing and iii) the applicability and scalability of the specific solution (feature, SW, HW, etc.) in real-life CAM environments and its potential to constitute a deployable solution in the near future.

The entire trialling effort of 5G-MOBIX across all CBCs/TSs has been focused on evaluating the XBI-CS pairs to provide insights into the best possible technologies and 5G network configurations that have enabled an optimised border-crossing experience for 5G enabled CAM vehicles/services.

Table 1 below provides the definitions of the 5G-MOBIX Cross-Border Issues (XBIs), as used by all 5G-MOBIX CBCs/TSs for their trials.

Table 1: Cross-Border Issues

XBI		Associated CS		
ID	**X-border Issue**	**CS_ID**	**Name**	**Test Site**
XBI_1	**NSA Roaming interruption:** With current networks, when a UE crosses a border, it tries to keep the connection to the previous network. This can result in a connection loss of several minutes. A new connection needs to be established and a new data session needs to be set up. This behaviour is even worsened because of steering of roaming that is implemented by MNO's. Trying to steer the UE to a preferred network and by doing so, deny certain roaming requests.	**CS_1**	S1 handover with S10 interface using an NSA network	**ES-PT, GR-TR**
		CS_2	Release and redirect using an NSA network	Proposed solution not field-tested
		CS_3	Release and redirect with S10 interface using an NSA network	Proposed solution not field-tested
XBI_2	**SA Roaming interruption:** Currently Roaming for SA networks has only been defined for basic roaming. No handover is specified and the equivalent of the S10 interface for EPC (N14) has not been referenced as a roaming interface. Because of these limitations it is expected that the same issues will arise, as seen in current networks, leading to disconnect times of minutes.	**CS_6**	Release and redirect using an SA network	**NL**
XBI_3	**Inter-PLMN interconnection latency:** Currently, operators interconnect using a GRX network used for both signalling and user plane data. This network extends over multiple countries and operators and is typically designed for high continuity and throughput, at the expense of low latency. Moreover, GRX connectivity may redirect traffic through far-away nodes (based on the GRX operator architecture), further increasing E2E latency, which is unsuitable for CAM applications.	**CS_7**	Internet-based Interconnection	**GR-TR**
		CS_8	Direct Interconnection	**ES-PT, GR-TR**
XBI_4	**Low coverage Areas:** Looking at current border areas, we see very low coverage areas because of sparse populations at the border. In addition, given the current regulations, operators must consider the maximum signal strengths allowed at the border. On both sides of the borders the same frequencies may be in use. Operators need to try and limit the interference. In addition, border areas are often sparsely populated, giving little incentives to provide for increased capacity or coverage in those areas. As a result, areas of low or no coverage may appear close to the border, threatening the CAM application continuity.	**CS_9**	Satellite connectivity	**FR**
XBI_5	**Session & Service Continuity:** When directing the UE to a new, closer, data network or to a neighbouring mobile network, the IP stack will likely change (other IP address and routing information). Current mobile networks do not give insight as to which location the UE is connected or when a change of location has happened. This can cause continuity issues or suboptimal latencies. A handover event can imply the change of network address with impact on running UDP/TCP communications and service disconnection. Moreover, a change of MNO in a roaming situation can imply a different set of protocols used in each domain e.g., IPv4 vs. IPv6. All this becomes especially evident in the case of edge computing, where latency requirements impose a switch to a different instance of an application server i.e., both ends of a communication session change. Under these circumstances, the applications' ability to adapt to the	CS_4	Multi-modem / multi-SIM connectivity - Passive Mode	**FR, DE, FI, CN**
		CS_5	Multi-modem / multi-SIM connectivity-Link Aggregation	**FR, FI, CN**
		CS_6	Release and redirect using an SA network	Proposed solution not field-tested
		CS_10	MEC service discovery and migration using enhanced DNS support	**ES-PT, FI**

	underlying network changes becomes increasingly important, to reduce the impact of mobility and ensure service continuity.	CS_11	Imminent HO detection & Proactive IP change alert	Proposed solution not field-tested
		CS_12	Inter-PLMN HO, AF make-before-break, SA	Proposed solution not field-tested
		CS_13	Double MQTT client	**ES-PT**
		CS_14	Inter-MEC exchange of data	**ES-PT, DE, NL, FR, CN**
		CS_15	Inter-server exchange of data	Proposed solution not field-tested
XBI_6	**Data routing:** When roaming, normally the data traffic will be routed to the home network and connected to the data network at home. Crossing the border from home-PLMN to a visited-PLMN will then lead to higher latencies. As an alternative it is also possible that the UE uses a local breakout roaming, connecting to the closest edge which will result in lower latency. However, setting up a connection to a new data network will take time which might result to a connection interruption and the potential loss of data. Also finding the closest edge might take time if the UE must perform a query to discover the closest edge after switching to the other PLMN.	CS_16	LBO NSA	**ES-PT, GR-TR**
		CS_17	HR NSA	**ES-PT, GR-TR**
		CS_18	LBO SA	Proposed solution not field-tested
		CS_19	HR SA	Proposed solution not field-tested
XBI_7	**Insufficient Accuracy of GPS Positioning:** Global Navigation Satellite Systems (GNSS) positioning cannot meet the stringent CAM requirements i.e., down to 20-30 cm accuracy. Moreover, it cannot be used while indoors (for example in tunnels. indoor parking/garages, or lower decks of multi-level bridges) and have strong limitations in dense urban environments. GNSS also lacks a refresh rate high enough to be used in safety critical applications. Without accurate geo-positioning, CAM applications that require external information based on absolute positioning cannot merge this information onto local maps with relative positions (distance to other vehicles/obstacles, lane position, etc.).	**CS_20**	Compressed sensing positioning	**NL**
XBI_8	**Dynamic QoS Continuity:** It is possible to adapt the service provisioning features/characteristics by the CAM application based on the current QoS network parameters. A sudden drop in the network connection quality may happen when the vehicles move from one MNO to the other in a cross-border area. This can lead to a performance degradation at the application level, hindering the full potential of CAM solutions.	**CS_21**	Adaptive Video Streaming	**DE**
		CS_22	Predictive QoS	Proposed solution not field-tested

XBI_9	**Geo-Constrained Information Dissemination:** A connected vehicle usually needs to receive traffic information directly related to its surroundings, not the whole flow of CAM messages exchanged through the edge computing node it is connected to. When it is travelling close to the border, it might also want to receive some data from neighbouring geographical areas covered by a MEC node located in another PLMN. Also, in this situation, not all CAM information exchanged through the neighbouring MEC is of interested to that specific connected vehicle. For instance, in a platooning application, the connected and autonomous members of the platoon solely need to exchange data with the platooning vehicles and possibly with some other vehicles and sensors in the vicinity. As a result, a geo-constrained information dissemination scheme should be devised in order to disseminate the relevant CAM data to the appropriate vehicles.	**CS_23**	Uu geobroadcast	**ES-PT, DE, NL**
		CS_24	PC5 geobroacast	**DE**
XBI_10	**Law enforcement interaction:** As automated driving technology becomes widely adopted, law enforcement entities across countries must be able to interact with automated vehicles on the roads. For instance, one can easily envision situations in which police officers may need to force a vehicle to stop if there is a suspicion that it is carrying a wanted individual. Dedicated communication procedures and protocols will need to be in place to ensure that authorities can communicate with vehicles, even if they originate from a different country being generally served by a foreign network provider	**CS_25**	mmWave 5G	**FR, KR**
XBI_11	**Network slicing applicability:** 5G enables the slicing of a single physical network into multiple virtual networks that can support different radio access networks RANs), or different service types running across a single RAN. Network slicing will maximise the flexibility of 5G networks, optimising both the utilisation of the infrastructure and the allocation of resources. Provide latency and reliability QoS for CAM by separating internet traffic on low priority slice.	**CS_26**	Network slicing	**NL**

2.2.1. Cross Border Recommendations for 5G for CAM

As a joint result of the research work previously carried out in task T6.1, much of which is included in deliverable D6.1 "*Plan and preliminary report on the deployment options for 5G technologies for CAM* ", and of the empirical results obtained during the numerous tests carried out in the CBC and TS, the main recommendations that the project considers useful for the optimisation and efficiency of future similar deployments are presented in this chapter. These have been classified based on the challenges posed (XBI) and the experiments carried out in the different scenarios with the proposed use cases.

It has been decided to prioritise the recommendations in the context of XBI and CS. In addition, we wanted to include other relevant recommendations, outside the context of XBI that have been appreciated during the different tests and that, from a more specific point of view, can benefit other deployments, whether in frontier environments or in simpler environments.

In conclusion, this section presents recommendations prioritised by the experts as priorities, which have been tested during the project life cycle, with special emphasis on the tests and trials carried out by both CBCs and by all the TSs. Supported on XBI and CS tested during the CBC and TS carried out trials.

2.2.1.1. Overview of technologies utilized in 5G-MOBIX

For the solutions applied in the cross-border environment, different technologies were available, all presented in the following deliverables, on the basis of which the recommendations were determined. Each of the CBC/TS participating in 5G-MOBIX has selected the appropriate technologies and network infrastructures to accommodate the selected use case categories. As a result, our recommendations consider what to do when using that specific stack of technologies in similar environments.

Further details of the technologies employed can be found in the following 5G-MOBIX project documents:

- *D2.1 - 5G-enabled CCAM use cases specifications.*
- *D2.2 - 5G architecture and technologies for CCAM specifications.*
- *D2.3 - Specification of roadside and cloud infrastructure and applications to support CCAM.*
- *D2.4 - Specification of Connected and Automated Vehicles.*

At a high level, the technologies integrated in the 5G-MOIX TS and CBCs are presented as below:

- Main architectural attributes → Components, configurations and Networks.
- Overview on CAM architecture and 5G technologies deployed per CBC / TS.
- CAM Infrastructure Components and vehicles at Cross-Border Corridors and Local Trial Sites.

As 5G-MOBIX focuses on cross-border deployments both Home Routing (HR) and Local Break Out (LBO) solutions were investigated, to support efficient roaming between different PLMNs, mostly in the two CBCs of the project, assisted by findings and testing at the TSs. Additionally, differentiated MEC and Edge computing deployments were available in the 5G-MOBIX sites, which facilitated trials with both configurations in the different test scenarios, resulting in optimal deployments for cross-border functionality. A brief overview of the main architectural attributes and network deployments in 5G-MOBIX is given inFigure 8 as a "birds-eye-view" of the technology deployed and tested per cross border corridor and trial site.

Table 2 provides a summary comparison of the advanced 5G architecture and technologies deployed in the different CBCs and TSs and of the 5G-MOBIX project. Finally, Table 3 provides an overview of CAM Infrastructure Components and Vehicles at CBCs and TSs. To enable 5G CAM use cases in the 5G-MOBIX project, different types of vehicles are used in each trial site. In total, 21 vehicles equipped with different technologies (cameras, 2D laser sensors, 3D laser sensors, GPS) were used.

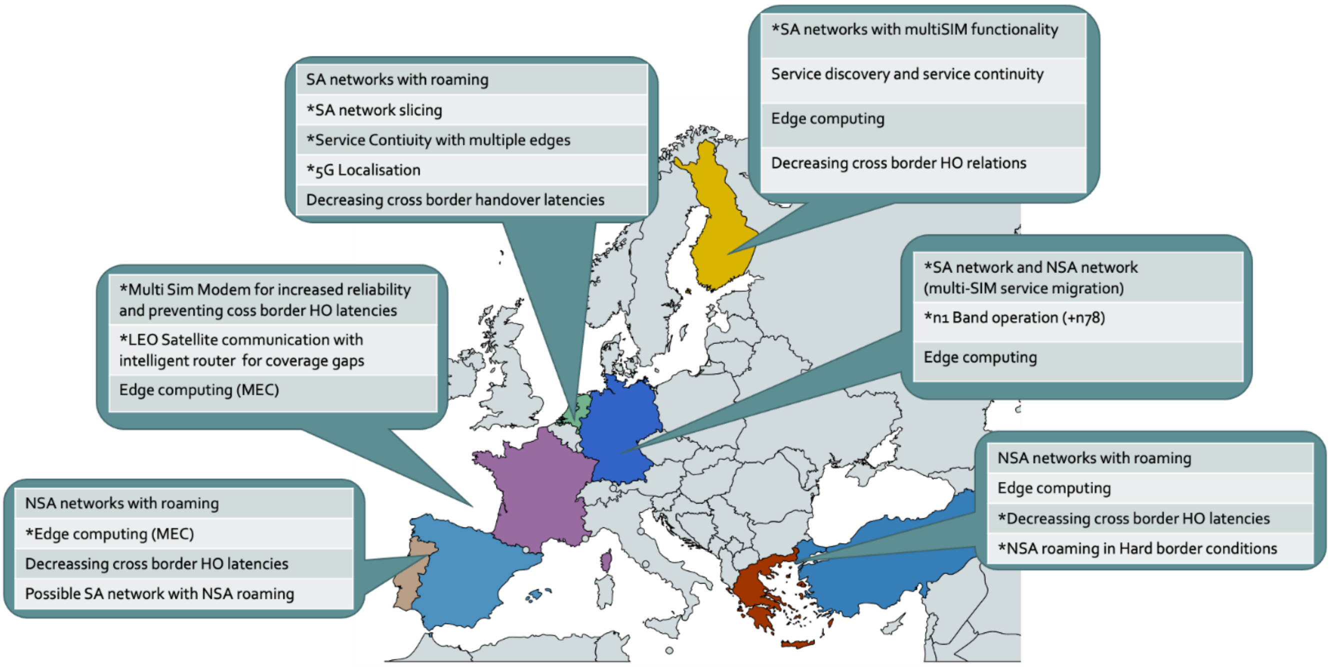

Figure 8: Technology overview per trial site (* indicates main differentiators).

Table 2: Overview of the main architectural attributes of the 5G-MOBIX sites

CBC/TS	3GPP Deployment Option	MEC	Roaming	Type	Commercial/ Test Components	Nº gNBs	Freq. Bands	Slicing	ITS centers / Cloud
ES	3x / (2)	Distributed (Far edge & central)	HR/LBO	NSA	Commercial: Transport network, 1x 4G RAN (MOCN) Test: 1x Core, 5G RAN, MEC	4	800 MHz (LTE B20), 1800 MHz (LTE B3) 2600 MHz (B7), 3.7 Hz (5G NR n78)	No	2 Cloud services operational , 1 ITS center operational
PT	3x / (2)	Distributed (Far edge & central)	HR/LBO	NSA (SA)	Commercial: IP and Transport network Test: 1x Core, 1x RAN, MEC	3	1800 MHz (LTE B3), 3700 MHz (5G NR n78)	No	2 Cloud services operational
GR	3x / (2)	Edge computing (SGi to PGW)	HR/LBO Coexistence with NB-IoT	NSA (SA)	Commercial: IP and Transport Network Test: 1x RAN, 1x Core, MEC	3	1800 MHz (LTE B3), 3700 MHz (5G NR n78)	No	2 Cloud services operational
TR	3x / (2)	Edge computing (SGi to PGW)	HR/LBO Coexistence with NB-IoT	NSA	Commercial: IP and Transport Network Test: 4x RAN, 1x Core	1	LTE B7 (2600) 20 MHz, NR n78G (3600 – 3700)	No	2 Cloud services operational
DE	3x / (2)	eRSU with MEC	N/A	NSA /SA	Commercial: 2x (NSA) Core + 1x RAN, Near Edge MEC Test: 1x SA Core, 1x RAN	2	2100 MHz (B1), 2100 MHz (n1) 3.6 GHz (n78)	No	1 ITS center operational
FI	3x / (2)	Commercial + SDN based	Multi-PLMN	NSA	Commercial: IP and Transport Network Test: 2x RAN, 2x Core, MEC	3	LTE B7 (2600) 20MHz, NR n78G (3600-3700)	No	1 Cloud services operational
FR	3x / (2)	Commercial Ericsson + MANO/SDN based distributed MEC (Edge)	Seamless Handover	NSA	Commercial: 1x NSA Core + 1x RAN, MEC Test: 1x SA Core + 1x RAN, MEC	3	NSA: 2.1 GHz (5G NR n1) + 800 MHz (LTE B20), 900 MHz (LTE B8), 1800 MHz (LTE B3) & 3.6 GHz (5G NR n78) + 1800 MHz (LTE B3), 2600 MHz (B7) SA: 3.7 - 3.8 GHz (n78)	No	1 Cloud services operational 1 ITS centre operational
NL	3x / 2	Multiple (Kubernetes based)	HR/LBO Multi-PLMN testing with peering	NSA/SA	Commercial: MEC Test: 2xRAN, 2xCore, MEC	8	2600 MHz (B7), 3.7 GHz (n78)	Yes	3 Cloud services operational
CN	3x / (2)	Yes	TBD	SA	Commercial: 1x Core Test: 3x RAN + 2x Core, 2x MEC	2	700 MHz (4G), 800 MHz (4G), 1800 MHz (4G) 2100 MHz (3G/4G), 2600 MHz (4G) 3500 MHz (5G), 3700-3800 MHz (n77), 2.6 GHz (n41)	Yes	1 Cloud services operational
KR	2	N/A	N/A Network S	SA	Commercial: 1x 4G RAN (MOCN), 1x 4G transmission Test: 3x 5G RAN, 3x Core, 3x MEC	3	3.7 GHz (5G NR n78) 27 GHz (5G NR n258), LTE: 800 MHz (LTE B20), 1800 MHz (LTE B3)	No	1 Cloud services operational

Table 3: Overview of the main network attributes of the 5G-MOBIX sites

CBC/ TS	C-V2X Direct PC5/Uu-based	CAM Messages	MEC Broker Deployment	Geoserver	MEC Applications	Roaming	Satellite Deployment
ES/PT	Uu	CAM, DENM, CPM, + custom messages	Implementation based on Mosquitto. Nokia solution.	Embedded in MEC Broker	VRU, Geoserver + MQTT broker, Remote driving and Registry	Cross-border	No
GR/TR	PC5 & Uu	CAM, DENM + custom messages	MQTT Ericsson solution.	-	Assisted zero-touch border crossing	Cross-border	No
DE	PC5 & Uu	CAM, CPM, DENM, MAP, SPAT + custom messages	Kafka, Mosquitto MQTT. Near Edge.	ETSI-based, part of device layer or as Geobroker (embedded in MEC Broker)	Signaling Server for Surroundview, EDM Service	Multi-SIM in NSA/SA	No
FI	Uu	Custom messages	Coordinator based on gRPC MEC Service Discovery.	-	HD Maps	Multi-SIM in SA	No
FR	Uu & PC5	CAM, DENM, CPM, MCM, MAP + custom messages	MQTT. Far/ Cloud Edge.	Embedded in MEC Broker	Data fusion, Risk analysis, Trajectory guidance, Predictive QoS	Multi-SIM in NSA	Yes
NL	Uu	CAM, DENM, MAP, SPAT, RTCM, IVI, CPM, MCM, + custom messages	Implementation based on Rabbitmq, MEC Discovery SSC M3.	Embedded in MEC Broker	Remote driving, collision avoidance application	Virtual cross-border	No
CN	PC5	BSM, MAP, RSI, RSM, SPAT. CAM	Mosquitto MQTT. ZTE solution.	- (addition planned)	Cloud-assisted driving	National	No
KR	Uu	Custom messages	No	-	-	No	No

Table 4: CAM Infrastructure Components and Vehicles at Cross-Border Corridors and Local Trial Sites

	CAM Infrastructure Components					
	Road sensors	RSU	RSU MEC (Far edge)	Number of vehicles	Level of automation	CAM Services
ES/PT	Traffic Radar, Pedestrian detector, 5G smartphones, ITS Centers, Remote Control Center	Yes	No	6	4	Complex Manoeuvres, Automated Shuttle, Public Transport
GR/TR	Camera	Yes	No	2	4	See-through streaming, zero inspection
DE	Camera, traffic analysis, road condition	Yes	Yes	4	4	EDM, GDM, Edge MANO, edge service discovery
FI	No	No	No	2	4	Remote driving, video streaming, video crowdsourcing, HD mapping, MEC service discovery
FR	Cameras, LiDAR	No	Yes	2	4	Infrastructure assisted lane change manoeuvre, different MEC Deployment options
NL	Cameras	No	Yes	3	4	Roadside assisted merging, Remote driving, Cooperative Collision Avoidance

2.2.1.2. Cross Border Recommendations

Below is a series of tables with the main results obtained during the tests carried out in the project. For more details about the tests and their analysis, it is recommended to consult the deliverables:

- *D3.7 - Final report on development, integration and roll-out*
- *D4.3 - Report on the corridor and trial site test activities*
- *D5.2 - Report on technical evaluation.*

The recommendations are presented including their associated XBI and CS tested during the trials and supported by a brief description of the lessons learned from their analysis.

XBI	**XBI_1 - NSA roaming interruption**
CS	CS1 - Handover with S10 interface using an NSA network
CBC/TS	ES-PT and GR-TR
Technical lessons learned	HR roaming provides radio handover times between 200 and 300 ms when crossing a cross-border area both in ES-PT and GR-TR, showing high repeatability and reproducibility. In the case of LBO, the need to set up a new data session extends the interruption time to the range of seconds with a magnitude directly depending on the number of antennas in the line of sight of the modem. Current progresses are focused to enable the trigger from the network side, instead of the modem, which is expected to reduce these times significantly.

Recommendation for XBI_1 - NSA roaming interruption:

Based on our analysis, it is recommend implementing **S1 handover with S10 interface interconnection when roaming in HR between two NSA networks provides optimal and stable service continuity in cross-border areas even for high latency-demanding CAM functions.** This configuration ensures optimal and stable service continuity in cross-border areas, even for high latency-demanding Connected and Automated Mobility (CAM) functions. By adopting this approach, the network can effectively handle the challenges associated with roaming and provide a seamless experience for users in cross-border regions.

XBI	**XBI_2 – SA roaming interruption**
CS	CS_6 – Release and redirect using a SA network
CBC/TS	NL
Technical lessons learned	LBO roaming between two SA networks has currently interruption times in the range of seconds because of technical challenges that the current state of the art in SA still does not solve.

Recommendation for XBI_2 – SA roaming interruption:

After analysing the results, it is recommended the implementation of release and redirect mechanisms using an NSA network in LBO. This approach is deemed feasible and adequate for CAM functions that do not necessarily require uninterrupted service continuity. By leveraging this method, CAM services can be efficiently redirected and released within the NSA network, allowing for optimized resource utilization and improved network performance. However, it is important to consider the specific requirements of each CAM function and ensure that the selected approach aligns with the desired level of service continuity.

XBI	**XBI_3 – Inter-PLMN interconnection latency**
CS	CS_7 – Internet-based interconnection CS_8 – Direct interconnection
CBC/TS	ES-PT and GR-TR
Technical lessons learned	E2E latencies in roaming depends on the connection between home and visited networks: • ES-PT achieves 100 ms on average at the application layer with the direct interconnection between TELEFÓNICA and NOS networks by interconnecting the central cores and the distributed cores through two transport networks. • GR-TR gets 80 ms on average at the application layer with the direct connection of the two edge sites in Alexandropouli and Kartal. When the communication is through the internet this value goes to 120 ms.

Recommendation for XBI_3 – Inter-PLMN interconnection latency

It is recommend implementing a **dedicated direct data network for interconnecting two neighbour networks.** This approach enables the establishment of **ad-hoc strategies that can be tailored to minimize delays while also considering the scalability of the solution**.

By creating a dedicated direct data network, it can address the immediate need for efficient and low-latency interconnection between the networks, providing a short-term but effective solution. However, it is crucial to assess the long-term scalability implications and explore alternative solutions that can accommodate future growth and evolving network requirements.

XBI	**XBI_4 – Low coverage areas**
CS	CS_9 – Satellite connectivity
CBC/TS	FR
Technical lessons learned	Low Earth Orbit satellite communication partially solves the coverage issue by providing functionality but with low data rates and high interruption times when moving from the antenna coverage. FR tests moving from 5G coverage to satellite coverage shows interruption times of a few seconds and throughputs of 100 kbps.

Recommendation for XBI_4 – Low coverage areas

During the trials, the challenge of terrestrial connectivity gaps **for CAM functions that require full coverage but not high demands in service continuity** has been effectively addressed. To this end, the implementation **of hybrid communication platforms combining 5G and satellite connectivity using intelligent routing** techniques is recommended. By leveraging both 5G networks and satellite connectivity, we can bridge terrestrial coverage gaps and ensure reliable communication for CAM services. Intelligent routing algorithms can be used to dynamically route traffic between the two communication media based on network conditions and coverage availability. This ensures that CAM functions receive the required connectivity even in areas where terrestrial networks may have limitations. It enables a seamless experience for users while optimizing the utilization of available network resources.

XBI	**XBI_5 – Session and service continuity**
CS	CS_4 – Multi-modem / multi-SIM connectivity, passive mode CS_5 – Multi-modem / multi-SIM connectivity, link aggregation
CBC/TS	DE, FI, FR and CN
Technical lessons learned	The multi-SIM solution in OBUs using multiple connections in the same session (link aggregation) provides higher service continuity, reliability and throughput than the one selecting the best or high priority connection (passive mode). With link aggregation, no packet loss reported by FR and CN and E2E latency of 20 ms reported by FR.

Recommendation for XBI_5 – Session and service continuity

CS_4 – Multi-modem / multi-SIM connectivity, passive mode

CS_5 – Multi-modem / multi-SIM connectivity, link aggregation

It is recommended the utilization of **multi-modem/multi-SIM OBUs supporting link aggregation capabilities to optimize performance in cross-border areas, particularly when there is a limited number of PLMNs available.** This approach involves equipping OBUs with multiple SIM slots, allowing for the aggregation of multiple network connections.

Using link aggregation, the OBUs can combine the bandwidth of multiple SIM cards and establish a more robust and higher-performing connection. This not only enhances the data throughput but also improves the reliability of communication in cross-border regions. While multi-modem/multi-SIM OBUs with link aggregation can effectively address the challenges of limited PLMNs, it is crucial to continuously evaluate and adapt to evolving network conditions and technologies. However, longer-term solutions should be explored to provide sustainable and scalable connectivity in cross-border areas, considering factors such as the availability of additional PLMNs and advancements in network infrastructure.

XBI	XBI_5 – Session and service continuity
CS	CS_10 – MEC service discovery and migration using enhanced DNS support
CBC/TS	ES-PT and FI
Technical lessons learned	Service interruption times when crossing areas with LBO roaming which needed a session migration are a function of the physical distance between the OBU and the DNS server. When the server is hosted in FI driving the vehicle in FI, the service migration takes 4.5 seconds but when the vehicle is driving in ES-PT takes 5.7 seconds.

Recommendation for XBI_5 – Session and service continuity

CS_10 – MEC service discovery and migration using enhanced DNS support

The **centralisation of information allowing automated and agile access to remote servers** is recommended. This approach involves the use of **MEC service discovery** mechanisms, which are a **suitable medium-term solution for CAM functions that do not necessarily depend on continuous service availability**.

By centralising information and leveraging MEC service discovery, CAM systems can efficiently locate and access remote servers as needed. This improves the responsiveness and agility of access to critical resources and services, thereby improving the overall performance of CAM functions. While centralisation of information and discovery of MEC services provides valuable medium-term benefits, it is essential to continually assess the evolving needs of CAM functions by exploring long-term strategies to ensure scalability, adapt to future technological advances and address the growing demand for service continuity in CAM deployments.

XBI	XBI_5 – Session and service continuity
CS	CS_13 – Double MQTT client
CBC/TS	ES-PT
Technical lessons learned	Double MQTT client is supposed to save time in the management of sessions during the handover by running separated connections, but the current high interruption times in LBO do not allow for the quantification of the possible efficiency of this solution.

Recommendation for XBI_5 – Session and service continuity

CS_13 – Double MQTT client

Based on experience during testing and expertise gained, the use of a dual MQTT client is discouraged, as it does not offer any advantage considering the current state of the art of LBO handover. The dual MQTT client concept, which implies the simultaneous use of two MQTT clients for communication, does not provide any significant advantage in terms of handover performance or efficiency in the LBO framework. Existing mechanisms and protocols for handover in LBO are designed to handle seamless transition and continuity of services without the need for a dual MQTT client.

It is considered important to focus on optimising the existing handover mechanisms and protocols within the LBO architecture, rather than introducing additional complexity by implementing a dual MQTT client. This could ensure an agile and efficient handover process without overhead and in a simpler way compared to the use of a dual MQTT client.

XBI	**XBI_5 – Session and service continuity**
CS	CS_14 – Inter-MEC exchange of data
CBC/TS	ES-PT, DE, FR, NL and CN
Technical lessons learned	Inter-MEC connections with fibre reduce the delay significantly when it is necessary to transmit traffic at the application layer. ES-PT in NSA (ES and PT MECs hosted 100 km away) and NL in SA (TNO and KPN MECS hosted 11 km away) obtains 3 ms when sending/receiving ETSI messages between the MQTTs hosted in the MECs on the two sides of the border. DE tests the interMEC RTT with commercial solutions getting 16 ms on average between MobileEdgeX platform located in Berlín and Amazon Web Services located in Paris.

Recommendation for XBI_5 – Session and service continuity

CS_14 – Inter-MEC exchange of data

It is indeed highly recommended to consider **direct fibre connections between MEC nodes as a means to significantly reduce communication delays**. However, it is important to note that this approach may raise scalability issues. With direct fibre connections between MECs, communication latency can be greatly reduced, resulting in improved throughput and responsiveness. This is especially advantageous in scenarios where low latency is critical, such as time-sensitive applications and services. Direct fibre connections between MECs require dedicated physical infrastructure and resources, which may not be feasible or cost-effective to deploy on a large scale. In addition, as the number of MEC nodes increases, the management and maintenance of direct fibre connections becomes increasingly complex.

Therefore, while direct fibre connections between MECs offer significant latency reduction benefits, it is essential to carefully assess the scalability requirements and potential challenges associated with deploying and managing the necessary infrastructure.

XBI	**XBI_6 – Data routing**
CS	CS_16 – LBO NSA CS_17 – NR NSA
CBC/TS	ES-PT and GR-TR
Technical lessons learned	The path followed by the messages when roaming in HR or LBO impacts on the E2E latency since HR maintains the session to the home network whereas LBO changes it to the visited one. As described in XBI_1/CS_1 and XBI_2/CS_6, HR experiments have shorter interruption times than LBO but the UL/DL latencies are 4ms on average lower in LBO than in HR, as tested in ES-PT and GR-TR.

Recommendation for XBI_6 – Data routing

HR is recommended for CAM functions that require uninterrupted service continuity. HR ensures that the user's home network handles signalling and routing, thus providing a seamless experience for CAM services that require continuous connectivity. On the other hand**, in scenarios where roaming occurs in the visited network, we recommend applying LBO optimisation. LBO aims to minimise E2E latency** by optimising the routing and communication between the UE and the network. By leveraging LBO techniques, the latency experienced during roaming in the visited network can be significantly reduced, improving the performance of CAM services.

It is essential to carefully assess the specific needs of each CAM service and configure the right combination of HR and LBO to provide an optimal user experience.

XBI	**XBI_7 – Insufficient accuracy of GPS positioning**
CS	CS_20 – Compressed sensing positioning
CBC/TS	NL
Technical lessons learned	NL tests 5G positioning solution based on mmWave 5G SA network configuration for line of sight and non line of sight with the antennas obtaining an accuracy of 0.3 m and 0.4-0.6 me respectively. These results significantly improve the >1m positioning achieved with 5G NSA network configuration.

Recommendation for XBI_7 – Insufficient accuracy of GPS positioning

During trials it has been confirmed that **large bandwidths enhance position accuracy**. Position accuracy is a critical factor in many applications, such as location-based services, navigation and tracking. By increasing the bandwidth of the communication channel, more data can be transmitted in each timeframe. This increased data throughput allows for more accurate measurements and calculations in positioning systems as well as faster sampling rates and data acquisition helping to reduce potential errors associated with noise and interference.

XBI	**XBI_8 – Dynamic QoS continuity**
CS	CS_21 – Adaptive video streaming
CBC/TS	DE
Technical lessons learned	Session-based applications can adapt dynamically their behaviour to the QoS provided by the network during the roaming stage. For instance, DE tests adaptive video streaming improving by 5%-20% the reliability by reducing the traffic when the network quality degrades.

XBI_8 – Dynamic QoS continuity

After carried out the trials and analysing the results obtained, it was found that **mechanisms at the application layer handle the network performance to increase reliable responsiveness**. The application layer plays a crucial role in managing the communication between end-user applications and the underlying network infrastructure. By incorporating specific mechanisms at this layer, organisations can optimise network performance and ensure a more responsive user experience.

Many of these mechanisms can detect and correct errors, retransmit lost or corrupted data, and ensure the successful delivery of messages at the application level, so that the application can remain responsive even under difficult network conditions.

XBI	**XBI_9 – Geo-constrained information dissemination**
CS	CS_23 – Uu geobroadcast CS_24 – PC5 geobroadcast
CBC/TS	ES-PT, DE and NL
Technical lessons learned	ETSI ITS-5G and ETSI ITS-PC5 support geo-networking protocols allowing the saving of network resources. Tests in ES-PT, DE and NL resulted in E2E latencies below 40 ms on average. On the other hand, DE tests show how PC5 communication gets lower latencies (around 20 ms on average) but its reliability degrades with the distance between sender and receiver and it is strongly affected by the line of sight conditions

XBI_9 – Geo-constrained information dissemination

The analysis of the results obtained from the trials has demonstrated that **Geo-broadcasting handles the publication of messages to optimize network resources with satisfactory results**. This approach has shown **satisfactory results in both 5G and PC5 communication scenarios, especially when PC5 communication is limited by distance.**

Geo-broadcasting involves broadcasting messages to a specific geographic area instead of individually addressing each receiver. This enables network resources to be used efficiently, minimising unnecessary overhead and improving overall network performance. In 5G networks, where communication distances may not pose significant constraints, geo-diffusion proves to be an effective strategy to optimise resource allocation and reduce signalling overhead. However, in PC5 communication scenarios, where the range is limited, the benefits of Geo-broadcasting are even more pronounced, as it helps to overcome distance limitations and efficiently distribute messages within the given area.

By implementing Geo-broadcasting, network operators could improve the scalability and efficiency of message delivery, resulting in better resource utilisation and higher overall performance.

XBI	**XBI_10 – mmWave applicability**
CS	mmWave 5G
CBC/TS	FR and KR
Technical lessons learned	Large bandwidth communications are depending on the distance to the gNB with a progressive degradation of the reference signal received power. Tests in KR achieved peaks

	of 209 Mbps in UL and RTT of 6.8ms on average with no packet loss whereas in FR the UL throughput is about 25 Mbps on average.

XBI_10 – mmWave applicability

As a recommendation based on the technical experience gathered in the different tests, the use of **mmWave technology is recommended for dedicated networks in areas with high user density, as it provides optimal performance over a range of a few hundred metres.** This mmWave solution (30 GHz) offers significantly higher bandwidth compared to traditional lower frequency bands. This higher bandwidth enables faster data transmission and supports the provision of high-capacity services in densely populated areas. This is particularly beneficial in situations where traditional cellular networks may suffer from congestion or have difficulty providing satisfactory data rates.

However, it is important to note that mmWave has limited propagation characteristics and is more susceptible to being blocked by environmental elements such as buildings or vegetation. Therefore, careful planning and deployment of mmWave infrastructure, including the placement of base stations or access points, is essential to ensure adequate coverage and performance.

XBI	XBI_11 – Network slicing applicability
CS	CS_26 – Network slicing
CBC/TS	NL
Technical lessons learned	NL explores the advantages of routing the high-priority traffic in a separate slice by setting the 5QI values in the gNB. The local breakout slicing setup is deployed in the communication between the broker MQTT hosted on the MEC and the vehicles where there is also background traffic (5 Mbps) exchanged via a low priority slice. The results show a significant decrease in latency (25 ms) compared to the baseline case, with no slicing, where the latency is around 350-400 ms.

XBI_11 – Network slicing applicability

Setting relative or absolute priorities between slices extends Quality of Service (QoS) capabilities. This network fragmentation allows the creation of multiple virtual networks on a shared physical infrastructure where each network slice can be customised to meet the specific requirements of different applications or user groups. By assigning priorities to these network slices, QoS capabilities can be further enhanced.

Relative priorities allow service levels to be differentiated between network slices by assigning higher priorities to certain segments. In this way, resources can be preferentially allocated to ensure better QoS for critical applications or high priority users, enabling more efficient use of resources and ensuring that important services receive the necessary network resources. Alternatively, absolute priorities can be assigned to network segments, establishing strict hierarchies for resource allocation. This approach guarantees a predefined level of QoS for certain segments, independent of the resource demands of other segments.

It is important to carefully define priorities based on the characteristics and requirements of each slice, taking into account factors such as latency, throughput, reliability and security.

From the technical results obtained, in summary, it has been observed that:

- Moderate outage times, on the order of 200 - 300 ms, and moderate E2E latency, on the order of 60 - 100 ms can be achieved with S1 handover with S10 interface mechanism in NSA networks, together with home routing and Internet-base interconnect. The LTE radio handover contributes 40-50ms to these values, and the rest is due to the 5G NR part.

- Direct inter-PLMN interconnection was further shown to significantly reduce latency, yielding values with mean and median values in the order of 45-50 ms.

- When the edge server resides in the source PLMN (under the HR configuration) the E2E latency improves significantly compared to a cloud server configuration (from 261 ms to 117 ms). In addition, more stable performance with less variation is observed.

- In the Local Break Out solution considered, the latency values are reduced (up to 40 ms) compared to Home Routed, because the vehicles are always connected to the nearest MEC. But it caused a significant service interruption, in the order of several seconds. The mobility outage time in the case of an LBO configuration is today highly dependent on the modem drivers, as there is still no standardized firmware to trigger session switching from the network side. The values obtained in both CBCs are in the order of seconds, which makes it quite difficult to run any CAM service safely.

- Multi-modem/multi-SIM solutions w/ Link Aggregation provide clear benefits over both single-modem/single-SIM and multi-modem/multi-SIM solutions w/ Link Selection, in terms of Reliability (32-57% packet loss reduction), Throughput (14-43% increase) and Latency (30-36% reduction).

3. CONCLUSIONS

The main recommendations are focused on **ensuring service continuity**. From a general deployment point of view, minimising signal, and coverage losses, which translate into service losses, by using appropriate network configurations and infrastructure support is one of the challenges addressed. To this end, collaboration and cooperation between industry and authorities is essential.

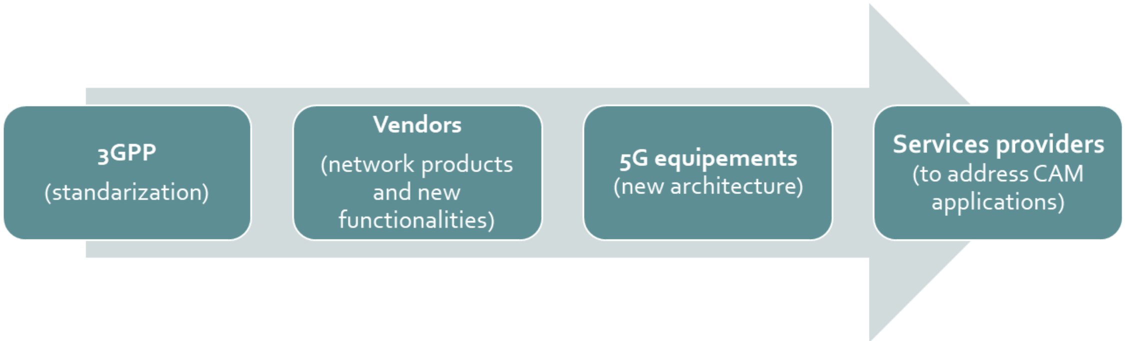

Figure 9: Fundamental cooperation between standardisation, vendors, and operators

3.1. Infrastructure Considerations

As already mentioned, there is a broad diversity of use cases with CAM functionalities, implying a different mix of bandwidth, latency, and reliability. A few CAM devices only support some use cases as they require a large amount of network resources, mainly where very low latency or high Uplink bandwidth is required. Dimensioning the network to support the required concurrency and to guarantee the mandatory performance for CAM use cases is a huge challenge. The spectrum bandwidth required for CAM functionalities is critical to support the initial deployment. Still, when borders between different countries are involved, some synchronisation between the different telecommunications and infrastructure operators must also be considered, as it helps improve the efficiency of the available resources and optimise the KPIs to the end user.

3.2. Equipment and Devices Considerations

The choice of the right equipment is crucial for the correct functioning of the overall CAM system. Not only does it need to be 5G enabled, but it also needs to be able to provide high enough data throughput to be useful in CAM use cases.

Concerning the non-infrastructure or non-radio equipment and devices, a distinction could be made between equipment that is integrated into vehicles (OBU, modem, antennas, etc...) and equipment that may be available to other road users, such as pedestrians (smartphones, wearables, etc.). In both cases, it is crucial that the equipment supports the features that 5G offers, as well as having the capacity for correct positioning.

To ensure optimal performance, it is crucial to meet the required standards. However, the importance of certain key capabilities may vary depending on the specific use case. It is also essential to consider machine-to-machine communication in addition to human-to-human or human-to-machine communication. For future usage scenarios, low-cost devices with a long operational lifetime are highly necessary.

In the case of the 5G enabled Android smartphones used in 5G-MOBIX as a pedestrian device for one of the variants of the vulnerable road user (VRU) use case, there were initial concerns about the accuracy of the GPS in commercial phones and how it could impact their use in CAM applications. The main requirements for this kind of devices are currently set by the ITU (International Telecommunication Union) for IMT-2020 systems [4]. This report also describes the key requirements for the minimum technical performance of IMT-2020 candidate radio interface technologies. Furthermore, depending on the definition of the different usage scenarios for 5G, these requirements have been divided into three key lines of work:

- **eMBB** (enhanced Mobile Broadband) which provides data rates of 1 Gbps.
- **URLLC** (Ultra Reliable Low Latency Communications) with and end-to-end latency of less than 10 ms.
- **mMTC** (massive Machine Type Communications) which allows the connection of a huge number of devices.

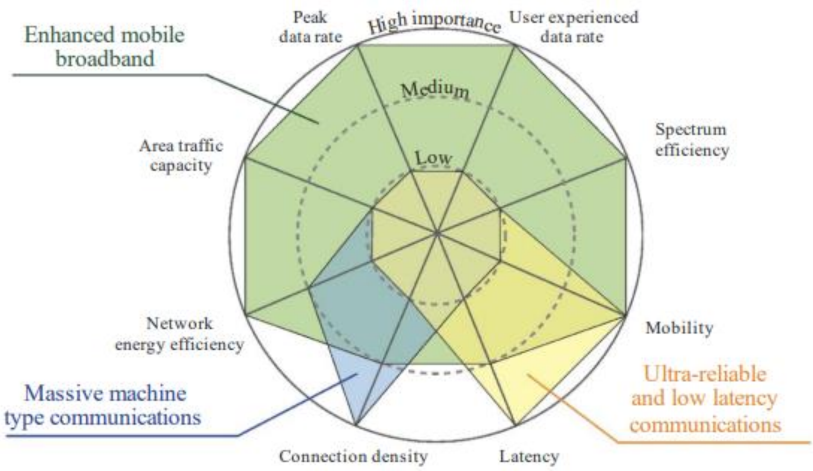

Figure 10: The importance of key capabilities in different usage scenarios. Source ITU

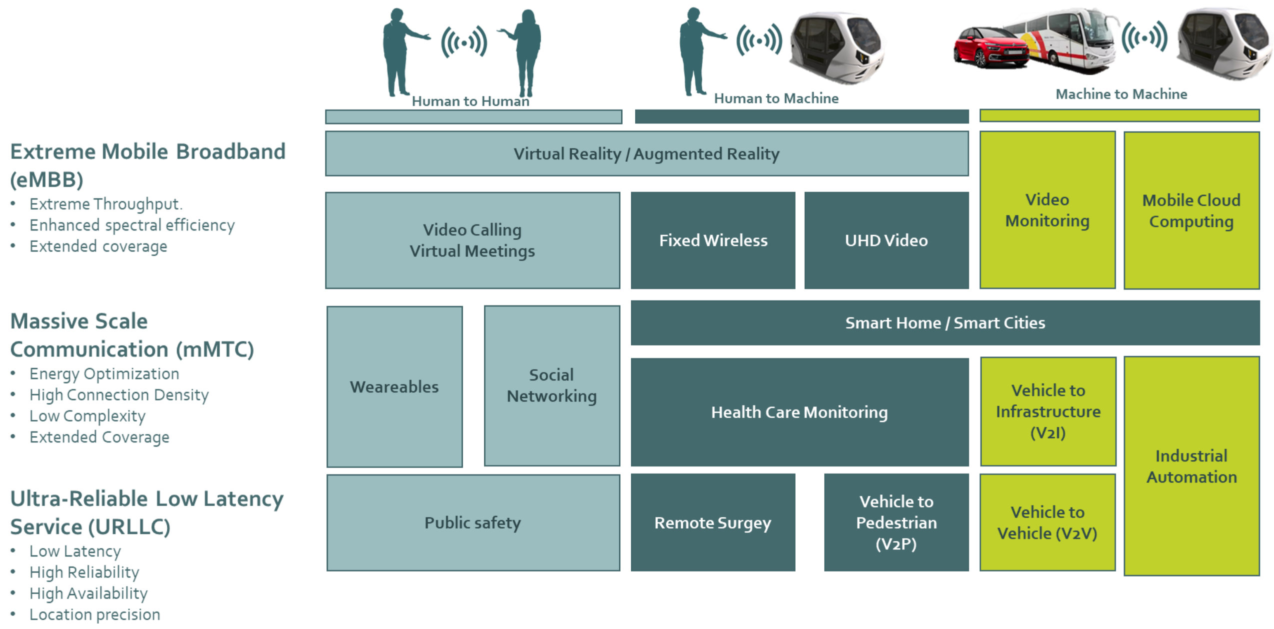

Figure 11: Summary of 5G Use Cases

3.3. Vehicles Considerations

Most modern vehicles are equipped with 4G/5G connectivity modems. Legacy vehicles can be upgraded with aftermarket modems, but to have such features, the vehicle harness and CAN (Controlled Area Network) bus must comply with modem assembly. The vehicle's interaction with the network must also be considered, so that the vehicle does not consider the network as a black box but as an element to be processed. This requires functions that interact with the mobile network and respond to certain changes in the network connection (e.g., reattach commands or scripts in the case of the in-vehicle modem with Local Breakout configuration).

Vehicles should have precise positioning information to be able to provide highly reliable information for 5G-CAM applications. Precise GNSS modules, 5G connectivity features, and sensor fusion algorithms should be considered for such functionality. The current most usual solution is that vehicles should have an onboard unit to receive the connectivity information. This unit should be connected to the CAN network to receive the vehicle data and receive GPS position. Also, it should process the received data and be able to communicate the information to the vehicle. A proper HMI (Human Machine Interface) should be placed in the vehicle to inform drivers about what is going on during 5G-CAM application in action.

3.4. General Technical Considerations

Some of the evaluation results obtained, presented in detail in the technical deliverables D3.7, D4.3 and D5.2, have shown that it is possible to achieve, using of different configurations and considerations, a network service continuity in border areas capable of allowing the correct development of CAM functions.

The key recommendations put forward in this analysis revolve around maintaining uninterrupted service in 5G for CAM. The focus is on addressing different challenges, such as mitigating signal and coverage disruptions and optimising network configurations and infrastructure support. All this from a perspective that encourages close collaboration and cooperation between all industry stakeholders and governance entities.

Several factors are critical to ensure service continuity in a cross-border context, so it is recommended to consider all the identified factors and challenges:

1. **Analysis** of the network environment identifying potential obstacles and evaluating the potential impact on existing networks.
2. **Analysis** of the capabilities of the equipment and infrastructure.
3. **Cooperation and collaboration** between different stakeholders, including MNOs, equipment vendors, service providers, and regulators.
4. **5G is not a one-size-fits-all solution** due to the fact different scenarios and use cases have different requirements.
5. **Interoperability and standardisation** of technical specifications and protocols, network security to disruptions, edge computing and network slicing.
6. **Infrastructure upgrades such** as base stations, antennas, roads and other equipment, as well as implementing new technologies such as network slicing and virtualization.
7. **Testing in real environments** to confront real challenges and problems greatly enhances the understanding of 5G technology and enables faster progress.
8. **Spectrum availability** to achieve the high data rates and low latency of 5G networks.
9. **New Security challenges** and data protection and privacy are in place to comply with local regulations and protect the confidentiality of customer information.

From the technical results obtained it has been observed that:

- The tests carried out in the two cross-border corridors have resulted in moderate outage times in the order of 200 - 300 ms and moderate E2E latency in the order of 60 - 100 ms with the S1 handover with S10 interface mechanism in NSA networks, together with home routing and Internet-to-base interconnection. LTE radio handover contributes 40-50 ms to these values, and the rest is due to the 5G NR part.

- Direct inter-PLMN interconnection was further shown to significantly reduce latency, yielding values with mean and median values in the order of 45-50 ms.

- When the edge server resides in the source PLMN (under the HR configuration) the E2E latency improves significantly compared to a cloud server configuration (from 261 ms to 117 ms). In addition, a more stable performance with less variation is observed.

In the Local Break Out solution considered, the latency values are lower (up to 40 ms) compared to Home Routed, because the vehicles are always connected to the nearest MEC. But it caused a significant service interruption, in the order of several seconds. The mobility outage time in the case of an LBO configuration is today highly dependent on the modem drivers, as there is still no standardised firmware to trigger session switching from the network side. The values obtained in both CBCs are in the order of seconds, which makes it quite difficult to run any CAM service safely.

Multi-modem/multi-SIM solutions with Link Aggregation provide clear benefits over both single-modem/single-SIM and multi-modem/multi-SIM solutions with Link Selection, in terms of Reliability (32-57% packet loss reduction), Throughput (14-43% increase) and Latency (30-36% reduction).

3.5. Final Considerations

This document analyses of CAM requirements and existing deployment options and projects aimed at 5G deployments and highlights the lessons learned during the 5G-MOBIX project deployment. These were first set out as a series of challenges to be addressed and recommended to be considered to reduce risks and costs and optimise future deployments. Starting from the identification of challenges, possible solutions and recommendations were put forward at a general level and in scenarios like those investigated in 5G-MOBIX.

In the future, V2X services will need to coexist with commercial networks, but there will be a separation between the resources allocated to CAM services and the rest of the customers. However, deploying new V2X services may take longer than previous commercial services due to the need for increased security and robustness.

To ensure good performance, high-density radio deployment is necessary in areas with heavy traffic such as highways. Conversely, in low-traffic regions like rural areas, lower density may suffice. Additionally, bandwidth should be made available on all types of roads with optimal coverage.

Regarding the devices, the optimal configuration for a modem, antenna and vehicle may differ greatly from other combinations of these components.

The potential deployment of Network Sharing for CAM services could be a good solution in some scenarios to share costs between several telecommunication operators that cannot afford the required initial investment. Some new CAM regulations could help this network sharing that now seems to be technically possible.

The correct processing and analysis of the data has enabled the correct interpretation of the results, which in turn has helped to avoid errors, identify potential failures, risks or problems more quickly, select and optimise the most appropriate equipment and devices, limit security breaches and generate a common knowledge base that can serve as a guide to improve the efficiency of similar 5G network deployments, increasing investment savings.

The automotive and CAM services industry must support all stakeholders by providing the necessary requirements for each of the functions and use cases they describe. Cooperation is essential in areas as diverse as lane marking, security and robustness against cyber-attacks, reduction of interference from elements of the road infrastructure, improvements in the positioning and availability of HD Maps, testing opportunities in real-world environments and the collection of revenue or payment of fees for CAM functions.

Cybersecurity plays an important role in ensuring the proper functioning of 5G technology and CAM functions in deployments and technology acceptance by all potential stakeholders. Ensuring validation, attestation and trust in the infrastructure and creating interoperability of trusted and secure domains is critical to ensure the continuity of future deployments.

The evolution and development of 5G is certainly more than a generational step; it is a revolution that opens a new world of possibilities for all technology industries. The possibility of having lower latency, wider channels, reliable responsiveness and the ability to connect many more devices simultaneously and in a limited area are some of the contributions of 5G that are clearly applicable to CAM.

5G has delivered a consistent experience in various scenarios, including ultra-high traffic volume density, ultra-high connection density and ultra-high mobility. Services such as enhanced mobile broadband (eMBB), which provides 1 Gbps data rates, ultra-reliable low latency communications (URLLC), end-to-end latency of less than 10ms, and massive machine-like communications (mMTC), which enables the connection of a huge number of devices, can make this a reality.

5G will continue to evolve and expand its global deployment plans as operators, enterprises and detractors work on its next phase. However, it will be some time before 5G networks are fully deployed and utilised. 5G is expected to scale rapidly after its launch in 2020, with coverage reaching just over a third of the world's population in five years, so the impact on countries, industry and their customers will be profound.

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5. ANNEX 1: DEPLOYMENT STUDY

The objective of this section is to provide an overview of the different costs to be considered when deploying 5G technology for CAM applications. DETECOM has been carried out a full ***Deployment Study***. In this deliverable, a summary of the most relevant aspects of that study is made and will also be provided as bibliographic data. As mentioned above, it is not possible to include further details for confidentiality reasons.

As requested by the European Commission, 5G-MOBIX has performed a deployment study that aims to address some key research questions and assess the amount of overall investment in the 5G roll-out required to achieve support for advanced CAM services within the next few years. Specifically, the project set out to assess the "investment delta" necessary, considering the already existing plans to roll-out 5G sites or to upgrade existing 4G sites, and the additional infrastructure that will need to be in place. To this end, the report is set out to provide answers to the following research questions (RQ).

- **RQ1**: What are the **traffic characteristics** that could be expected by 2023 and 2025?
- **RQ2**: What are the **exact needs of CAM services at border areas** and the CAM use-cases' detailed requirements?
- **RQ3:** What are the **already planned investments in physical & digital infrastructure** to be deployed in the Cross Border areas?
- **RQ4**: What is the **deployment "delta" between currently planned investments** and the necessary investments to deliver full coverage for the CAM use-cases?
- **RQ5:** What is necessary with regards to networking, preparation for market and business risks, enablers, market analysis, and **competitive intelligence**?
- **RQ6:** What are any **assumptions and projections** that can be made **towards 2030**?

DETECON[1] undertook the completion of this study on behalf of 5G-MOBIX, by performing a variety of stakeholder interviews, extensive simulations on the Cross Border Corridors and with regular input stemming from 5G-MOBIX activities and trials. Specifically, the study was completed for ~40 km stretches of road, 20 km on each side of the border, of each of the following five CBCs (Figure 12):

- **ES-PT:** Tui/Valença (Vigo – Porto)
- **GR-TR:** Kipoi/Ipsala (Alexandroupoli – Kesan)
- **DE-NL:** Veldhuizen (Emmerich – Arnhem)

- **FI-NO:** Kilpisjärvi (Skibotn – Muonio)
- **ES-FR:** Le Perthus (Figueres – Perpignan)

[1] DETECON main website: https://www.detecon.com/ (Accessed June 2022).

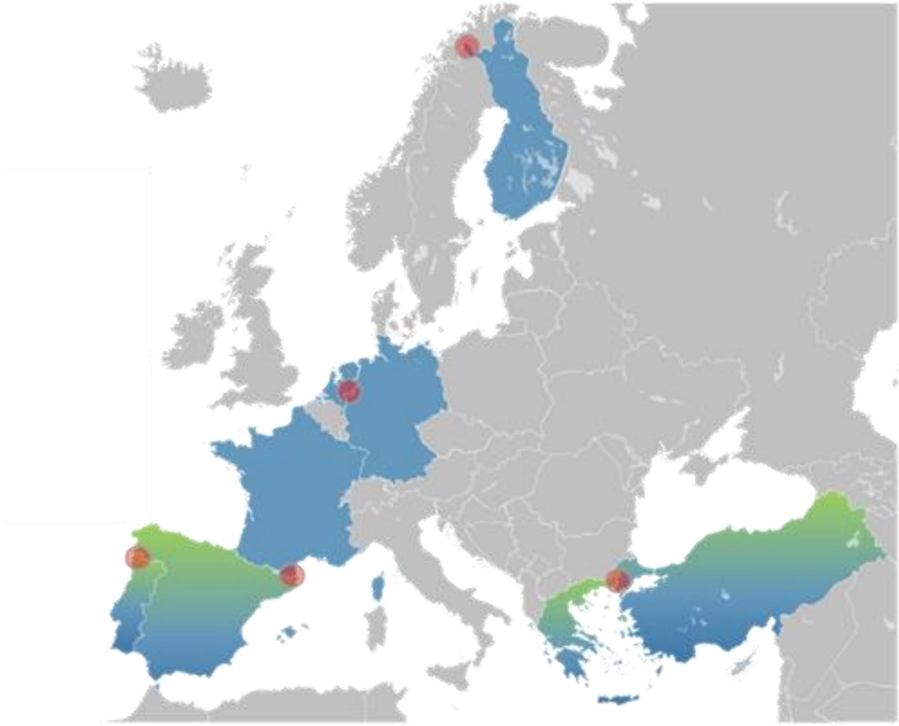
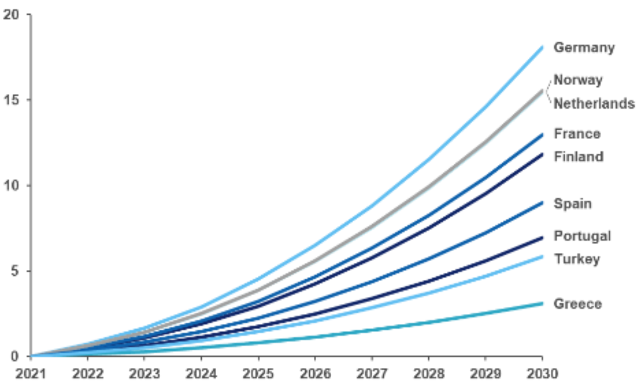


Figure 12: Geographical location of CBCs selected for the deployment study.

The study performed an analysis of the expected fleet share of CAVs (Figure 13), assuming a SAE L3+ level of automation, in order to assess the daily number of vehicles requiring 5G for advanced CAM Services, based on existing data on the traffic characteristics of the CBC countries.

Fleet share of Level 3+* by country with country adj. (all vehicle types):



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Finland	0,00%	0,48%	1,08%	1,90%	2,95%	4,23%	5,76%	7,53%	9,54%	11,81%
France	0,00%	0,53%	1,18%	2,08%	3,23%	4,64%	6,32%	8,26%	10,47%	12,96%
Germany	0,00%	0,73%	1,65%	2,90%	4,51%	6,48%	8,81%	11,52%	14,60%	18,08%
Greece	0,00%	0,13%	0,28%	0,50%	0,78%	1,12%	1,52%	1,98%	2,51%	3,11%
Nether-lands	0,00%	0,63%	1,41%	2,48%	3,86%	5,54%	7,53%	9,85%	12,49%	15,46%
Norway	0,00%	0,63%	1,42%	2,50%	3,88%	5,58%	7,59%	9,92%	12,58%	15,57%
Portugal	0,00%	0,28%	0,63%	1,11%	1,73%	2,49%	3,38%	4,42%	5,61%	6,94%
Spain	0,00%	0,36%	0,82%	1,44%	2,24%	3,22%	4,38%	5,72%	7,25%	8,98%
Turkey	0,00%	0,24%	0,53%	0,94%	1,46%	2,09%	2,84%	3,72%	4,71%	5,84%

Source: Detecon Analysis; ACEA; OICA; McKinsey; Deloitte
Within this study, CAVs & CAM are defined as level 3-5 as per SAE definitions.

Figure 13: Estimated fleet share per country for SAE L3+ vehicles, up to 2030

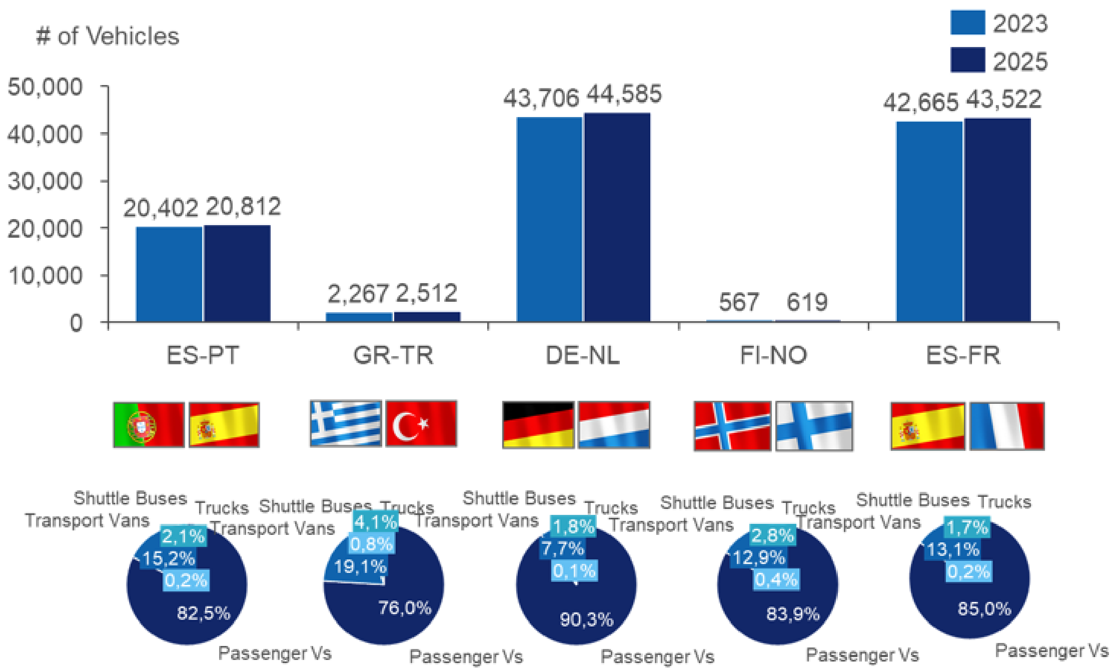


Figure 14: Traffic forecasts and vehicle type shares per CBC

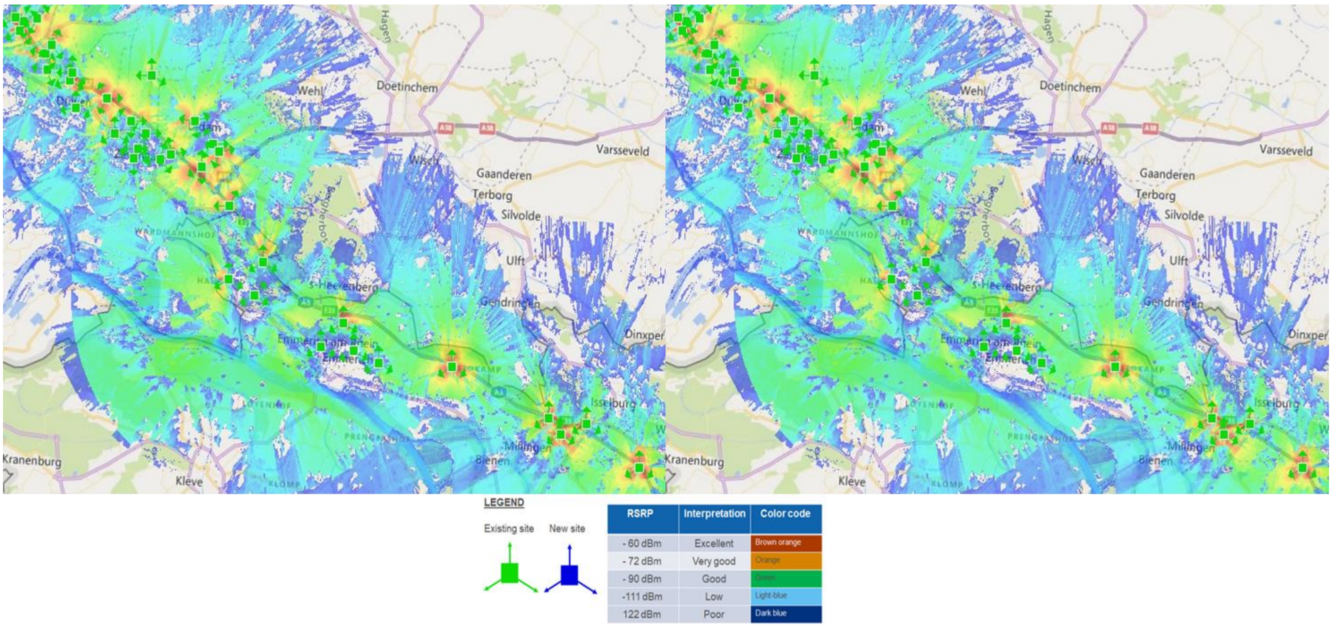
The locations of existing base stations were identified through stakeholder interviews or through publicly released data. Figure 15 below illustrates the preliminary results for the DE-NL cross-border corridor. Radio planning results showed that:

- Existing sites that could be upgraded to 5G: 12 on the German side, 2 on the Netherlands side.

- 12 new sites were added and distributed along the road to provide seamless coverage: 8 along the German stretch of the corridor, 4 along the Netherlands stretch of the corridor.

Figure 16, Figure 17 and Figure 18 illustrate some of the cost estimates provided in the study. Among the estimated costs are the average annual operational expenditures (OPEX), as well as the average capital expenditures (CAPEX) for new or upgraded 5G sites. Figure 18 illustrates a high-level breakdown of roll-out activities. Although differences exist among the different locations, there are some shared characteristics. In all locations, for example, site acquisition was the most time-consuming activity. The roll-out also required the cooperation of multiple different departments within a telco provider organisation.

The full Deployment Study report will be available on 5G-MOBIX website [[https://5g-mobix.com/resources/deliverables]



RSRP	Interpretation	Color code
- 60 dBm	Excellent	Brown orange
- 72 dBm	Very good	Orange
- 90 dBm	Good	Green
-111 dBm	Low	Light-blue
122 dBm	Poor	Dark blue

Figure 15: Suggested deployment in the DE-NL Cross Border Corridor.

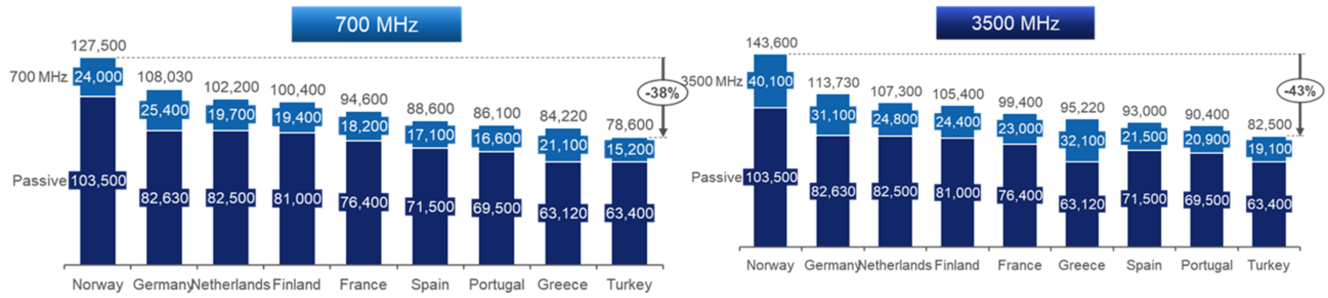


Figure 16: CAPEX costs per base station. Dark blue denotes costs for passive equipment, light blue denotes costs for active equipment. Estimates for the 700MHz and 3500MHz bands.

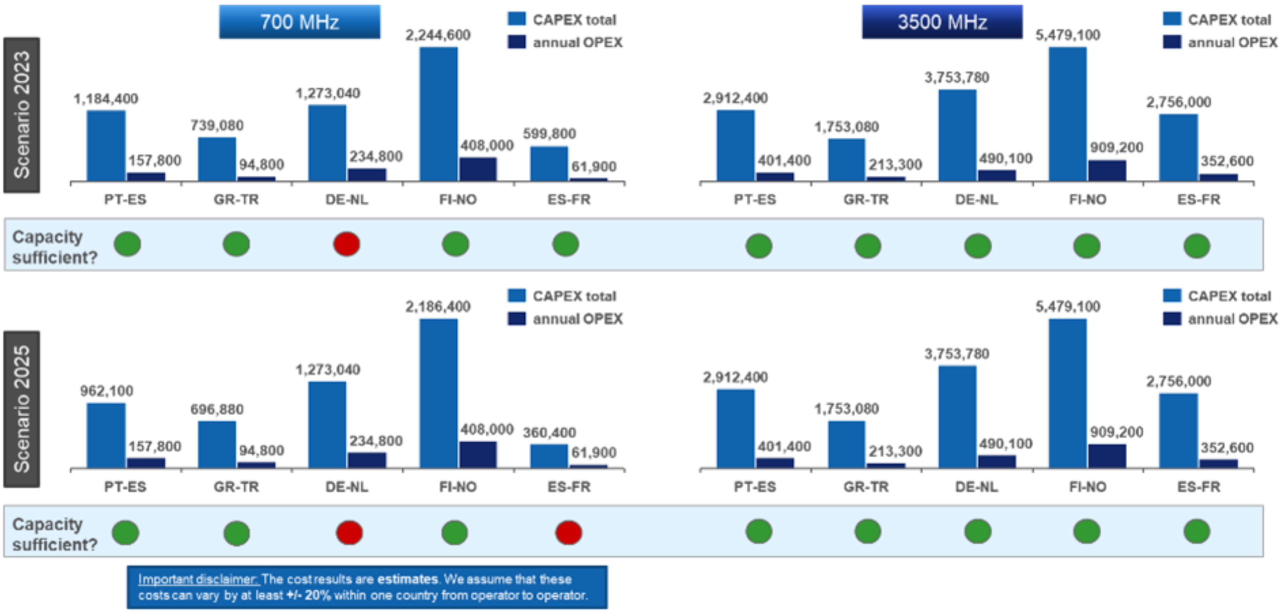


Figure 17: Total estimated CAPEX for each corridor country and average annual OPEX.

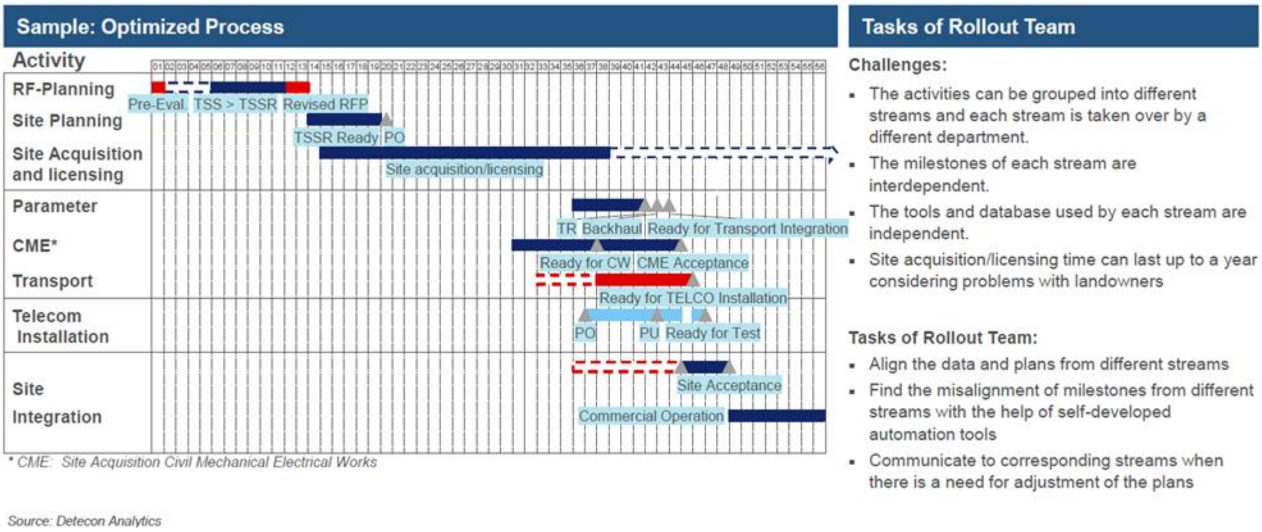


Figure 18: High-level description of roll-out patterns. Site acquisition introduces the largest time uncertainty.