5GMOBIX

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

D5.2

Report on technical evaluation

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ABBREVIATIONS

Abbreviation	Definition
3GPP	3rd Generation Partnership Project
ACKS	Acknowledgment messages
AD	Automated Driving
AMC	Adaptive Modulation and Coding
APN	Access Point Name
ARFCN	Absolute Radio-Frequency Channel Number
AWS	Amazon Web Services
bps	bits per second
BCCH	Broadcast Channel
BSM	Basic Safety Message
C-ITS	Cooperative Intelligent Transport System
C-V2X	Cooperative Vehicle to Everything
CoCa	Cooperative Collision Avoidance
CC	Component Carrier
CAM	Connected and Automated Mobility
CAM	Cooperative Awareness Message
CAV	Connected and Automated Vehicle
CBC	Cross Border Corridor
CBR	Constant Bit Rate
CDF	Cumulative Distribution Function
CI	Confidence Interval
CN	China
CPM	Collective Perception Message
CPU	Central Processing Unit
CQI	Channel Quality Information
CS	Considered Solution
CTS	Centralized Test Server
Dx.x	Deliverable x.x
DCCH	Dedicated Control Channel
DE	Germany
DL	Down Link
DNS	Domain Name System
DSRC	Dedicated Short-Range Communication
DU	Distributed Unit

eNB	evolved Node B
ePLMN	equivalent Public Land Mobile Network
eRSU	enhanced Road Side Unit
E2E	End to End
EARFCN	E-UTRA Absolute Radio Frequency Channel Number
EC	European Commission
EDM	Edge Dynamic Map
ES	Spain
ETSI	European Telecommunication Standards Institute
EVM	Error Vector Magnitude
FDD	Frequency Division Duplex
FI	Finland
FR	France
gNB	next generation NodeB
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GR	Greece
GRX	GPRS Roaming eXchange
H	Home
HARQ	Hybrid Automatic Repeat Request
HD	High Definition
HR	Home Routed
HSS	Home Subscriber Server
IP	Internet Protocol
IPX	Internet Protocol eXchange
ITS	Intelligent Transport System
km	kilometre
KPI	Key Performance Indicator
LBO	Local Break-Out
LDNS	Local Domain Name Server
LOS	Line Of Sight
KR	Korea
LEO	Low Earth Orbite
LTE	Long-Term Evolution
m	meter
mmWave	millimetre Wave
ms	millisecond

MeNB	Master evolved Node B
MAC	Medium Access Control
MCC	Mobile Country Code
MCM	Manoeuvre Coordination Message
MCS	Manoeuvre Coordination Service
MEC	Mobile Edge Computing
MIP	Mapped Internet Protocol
MME	Mobility Management Entity
MNC	Mobile Network Code
MNO	Mobile Network Operator
MQTT	Message Queuing Telemetry Transport
NA	Not Applicable
NL	Netherlands
NLOS	Non-Line Of Sight
NR	New Radio
NSA	Non-Standalone Architecture
OBU	On Board Unit
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency Division Multiplexing
OWD	One Way Delay
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDU	Protocol Data Unit
PGW	Packet Gate Way
PLMN	Public Land Mobile Network
PPP	Public Private Partnership
PT	Portugal
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
QAM	Quadrature Amplitude Modulation
RA	Radio Access
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RMSE	Root Mean Square Error
ROC	Remote Operations Centre
RRC	Radio Resource Control

RSRP	Reference Signal Received Power
RSU	Roadside Unit
RTK	Real Time Kinematic
RTT	Round Trip Time
SgNB	Secondary next generation NodeB
SA	Standalone Architecture
SDU	Service Data Unit
SGW	Serving Gate Way
SIM	Subscriber Identification Module
SNR	Signal Noise Ratio
SSC	Session and Service Continuity
TAC	Tracking Area Code
TCA	Test Case Agnostic
TCP	Transmission Control Protocol
TPC	Transmit Power Control
TDD	Time Division Duplex
TE	Technical Evaluation
TR	Turkey
TS	Trial Site
TTI	Transmission Time Interval
UCC	Use Case Category / Use Case Categories
UDC	User Data Consolidation
UDP	User Datagram Protocol
UE	User Equipment
UL	Up Link
URLLC	Ultra Reliable Low Latency Communications
US	User Story / User Stories
USB	Universal Serial Bus
V	Visited
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2X	Vehicle to Everything
VDS	Vehicle Discovery Service
WebRTC	Web Real-Time Communication
Wi-Fi	Wireless Fidelity
WP	Work Package
X-border	Cross-border

XBI	Cross-Border Issue

EXECUTIVE SUMMARY

Context

This is deliverable D5.2 "Report on technical evaluation" of the 5G-MOBIX project. The main objective of the deliverable is to report on the technical evaluation results of the 5G trials performed across two cross-border corridors (CBC) (Spain -Portugal and Greece – Turkey) and six local trial sites (TS) in Europe (Germany, Finland, France and Netherlands) and Asia (China and Korea).

Relevance to service continuity in cross-border context

The technical evaluation process focused on a series of key technical challenges (termed as *X-Border Issues*, *XBIs*) and corresponding technical solutions (termed as *Considered Solutions*, *CS*), that the consortium identified as of primary importance towards the support of service continuity for connected and automated mobility (CAM) services in the considered cross-border environments. The CSs at hand essentially correspond to a series of deployment and configuration options for the 5G system. Summarizing the most important challenges and corresponding solutions evaluated[1]:

- **Radio Handover Interruption**, where the challenge relates to the steering of the handover procedure involving aspects that have an impact on the resulting interruption time e.g., the triggering of the handover process, the identification/selection of the frequency, the establishment of the appropriate control plane state, etc. On this front, the project focused on a **S1 handover with S10 interface** solution in 5G Non-Stand Alone (NSA) Option 3x deployments, and a **Release and Redirect** approach in 5G Stand Alone (SA) deployments.

- **Data Routing**, where the project focused on the assessment of the **Home Routing (HR)** and **Local Break Out (LBO)** configurations. The target was to quantify the trade-off between the higher latencies expected when user plane traffic always traverses the Home PLMN (Public Land Mobile Network) in HR, and the lower latencies but higher service disruption times expected when routing is re-configured so that user plane traffic traverses the Visited PLMNN gateway in LBO. It is important to note that the LBO

[1] In addition to these main focus areas, the project also engaged in the investigation of additional technological options such as the ability of Satellite or mmWave communication to support seamless CAM services. The maturity level of the available implementations/devices was rather low, not allowing to derive conclusions generic enough to characterize the corresponding technology. However, our findings are reported in the document.

solution evaluated followed a break-before-make principle, equivalent to SSC (Session and Service Continuity) Mode 2[2].

- **Inter-PLMN interconnection,** where the focus is on the quantification of latency savings expected by the **direct interconnection** of neighbouring PLMNs, over leased lines, against the typical GRX **Internet-based interconnection**.

- **Service & Session Continuity,** is a broader challenge category, where the project investigated a set of technical solutions that focus on UE side or application-level deployment or configuration options towards service continuity including: (i) **multi-modem/multi-SIM connectivity** (with link selection of link aggregation); (ii) **MEC service discovery & migration**; (iii) **adaptive video streaming,** (iv) **MEC node direct interconnection**.

- **Network slicing,** where the technical evaluation process focused on the experimental validation of network slicing as a technical means to guarantee quality of service for CAM services.

The technical evaluation of the aforementioned challenges and corresponding solutions, took place in the context of a wide set of full-fledged CAM services across all five (5) 3GPP (third Generation Partnership Project) Use Case Categories[3]: (i) Advanced Driving; (ii) Vehicles Platooning; (iii) Extended Sensors; (iv) Remote Driving; (v) Vehicle Quality of Service Support. As such:

- The derived results correspond to Key Performance Indicators (KPIs) mainly assessed on an end-to-end basis e.g., Latency, Throughput, and were evaluated in the context of pre-specified target values. However, additional control plane metrics were measured for the investigation of handover related aspects e.g., identifying mobility interruption times orthogonally to traffic patterns.

- The overall system setup/configuration included co-existing solutions across several technical challenges (where applicable) e.g., S1 handover with S10 interface, along with a HR configuration with Internet-based inter-PLMN interconnection. Diverse test cases were devised for this reason, so as to allow the direct comparison of individual configuration options e.g., a LBO configuration in the above example.

Lessons Learned

In the following, it is summarized the main quantitative findings of the technical performance evaluation:

[2] 3GPP, Technical Specification Group Services and System Aspects, TS 23.501 System architecture for the 5G System (5GS), Initial Planned Release 15

[3] 3GPP, Technical Specification Group Services and System Aspects, TS 22.186 Enhancement of 3GPP Support for V2X Scenarios, Initial Planned Release 15

- The S1 handover with S10 interface mechanism in 5G NSA Option 3x deployments, along with Home Routing and Internet-based interconnection configurations, yield moderate mobility interruption times, in the order of 200-300ms. The LTE radio handover part contributes 40-50ms to these values, with the rest owing to the 5G NR part. This configuration setup further also yielded moderate end-to-end latency values i.e., 60-100 ms.
  - 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. This corresponds to a 29-51% reduction across the various evaluation scenarios.
  - Edge computing was shown to reduce latencies by 37-55%, and also improving the stability of values observed, compared to the use of centralized cloud resources reached over the public Internet.
- Network layer re-configurations i.e., UE IP address and packet gateway / user plane function change, in the considered Local Break Out solution, was proved to yield a significant service disruption, in the order of multiple seconds. On the other hand, LBO was found to reduce end-to-end latency values down to 40 ms.
- 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).
- Discovering the local MEC service instance (upon an inter-PLMN handover) was shown to require around 45-50 ms using local DNS. Depending on the application at-hand this latency may add to total service disruption, on top of radio handover and network layer (Data Routing: LBO) reconfigurations.
- The direct interconnection of MEC nodes over a highly provisioned (leased) line (orthogonally to the inter-PLMN interconnection) results in low/negligible latency impact i.e., additional latency for traversing the inter-MEC hop is in the order of 15-20ms.
- Application-layer protocols used in several services i.e., WebRTC, MQTT, resulted in considerable service disruption when session re-establishment was required, upon a mobility event e.g., 4-5 s in the case of WebRTC.
- Adaptive video streaming was shown to improve reliability (by 5 - 20%) when network conditions degrade i.e., by allowing less data to be transferred.
- Network slicing was shown to guarantee QoS, as long as the terminals/UEs are carefully configured to not pollute network slices with background traffic i.e., traffic other than the one to be protected. Testing procedures revealed the immaturity of commercially available UE implementations (devices), which showed unexpected behaviours.

Conclusions

A series of observations and conclusions is reached based on the evaluation findings. These are presented here, clustered with respect to the ecosystem stakeholder primarily affected:

Mobile Network Operators (MNOs)

- S1 handover with S10 interface along with Home Routing solutions, in 5G NSA Option 3x, strike a good balance between latency and overall service disruption for the vast majority of CAM services evaluated, including services traditionally implemented through V2V communications e.g., Platooning. This does not hold for very low latency CAM services (i.e., well below 50-60ms). Direct interconnection links can provide some room for lowering this threshold (see also next). It must be noted however that these conclusions have been derived in the context of a single CBC environment: multi-CBC mobility scenarios (not tested) i.e., long trajectories across Europe, are expected to yield increased latency values in the HR setup, while the establishment of direct interconnection lines, which are bilateral, are not expected to (financially) scale in the presence of multi-PLMN mobility across European MNOs.

- 5G standards[4] specify the solution for the optimal balance between service disruption and latency in the form of SSC mode 3 i.e., "make-before-break" approach. However, current implementations (core and UE sides) only support SSC mode 2 ("break-before-make") which was shown to render LBO impractical in terms of the resulting disruption. Hence, we conclude that the readiness level of LBO solutions is rather low at the moment.

Original Equipment Manufacturers (OEMs) / CAM Service Providers

- Multi-modem/multi-SIM UEs/OBU terminal devices appear to offer a viable option, as long as they support link aggregation.

- Adapting data rate requirements at the service/application level, according to the perceived network performance, can provide a non-negligible improvement of service reliability.

- The design of several application-level protocols, typically used in the implementation of CAM services is unsuitable for the considered CBC mobility environments. Close investigations concluded that session re-establishment negotiations result in considerable service disruption.

- Network slicing can guarantee QoS, but terminal device implementation has to improve so as to provide stability.

Recommendations

[4] 3GPP, Technical Specification Group Services and System Aspects, TS 23.501 System architecture for the 5G System (5GS), Initial Planned Release 15

Mobile Network Operators (MNOs)

- S1 handover with S10 interface, along with HR are the recommended baseline 5G NSA Option 3x configuration options for a plethora of CAM services. The recommendation holds for single-CBC environments.

- The establishment of Direct Interconnection links is recommended for single-CBC environments. Scalability/complexity concerns appear in multi-CBC/pan-European mobility environments, and should be carefully assessed on a techno-economic front.

- The establishment of direct MEC interconnection links is also recommended to facilitate session migration in future LBO-enabled environments.

Original Equipment Manufacturers (OEMs) / CAM Service Providers

- Multi-modem / multi-SIM UEs are recommended for services expected to operate in small scale i.e., only a 2-3 PLMNs involved. This recommendation holds on the short-medium term, until SSC mode 3 becomes available (depends on the vendors exact roadmap). Balancing the costs of this solution against the amortization period is required in order to better understand the market need and corresponding delivery of SSC mode 3 by vendors.

- Improvements/optimizations are needed in several of the widely used application-enabling protocols such as MQTT and WebRTC. These improvements should be seriously taken into account during service design and development.

- Extensive terminal device testing is strongly recommended so as to ensure operational stability.

- Coordination between Service Providers/OEMs and MNOs is recommended, in what concerns service discovery aspects in the context of LBO configuration. Local DNS/service discovery should be available and always aligned with the underlying routing configuration i.e., pointing to the closest server. DNS caching (on device) should also be considered in an effort to avoid service discovery latencies.

Overall, the obtained results show that 5G can deliver a capable solution that supports cross-border mobility making possible significant improvements in CAM performance for more users and more services. Services with higher needs can be adapted to the current network status with the collaboration between telecom network and service providers. This analysis opens up a horizon of technological improvements, solutions and services that will significantly enhance universal mobility.

1. INTRODUCTION

1.1. 5G-MOBIX concept and approach

5G-MOBIX aimed to showcase the added value of 5G technology for advanced connected and automated mobility (CAM) use cases and validate the viability of the technology to bring automated driving (AD) to a high level of vehicle automation. To do this, 5G-MOBIX executed CAM trials along cross-border and inland corridors using 5G technological innovations to qualify the infrastructure and evaluate its benefits in the context of CAM services across borders. To this end, the project first defined critical scenarios needing advanced connectivity provided by 5G, and the required features to enable some advanced CAM use cases. The matching of these advanced CAM use cases and the expected benefits of 5G was tested during trials on 5G corridors in different European countries as well as in Turkey, China and Korea. The trials allowed 5G-MOBIX to conduct technical evaluations to assess the effects of roaming/ handover events on the delivery of timely, continuous and seamless CAM services in cross-border environments.

1.2. Purpose and structure of the deliverable

The main purpose of this deliverable is to provide a complete set of results on the cross-border mobility trials carried out in the 5G corridors deployed in Europe and Asia (China and South Korea). It belongs to WP5 (Evaluation) and details the methodology followed for the technical evaluation as well as the results obtained.

The document is structure as follows:

- **Section 2, Evaluation Methodology**, outlines the complete evaluation methodology with pointers to the previous deliverables that provided specific information about the evaluation framework.
- **Section 3, CBC / TS Evaluation Objectives,** presents the evaluation targets of the cross-border corridors and trial sites recapping the 5G configurations deployed, test cases executed and cross-border issues analysed.
- **Section 4, Evaluation Results,** provides the results on the cross-border issues across all the 5G configurations deployed among the cross-border corridors and trials sites.
- **Section 5, CAM Service Support: Target vs Measured KPI values,** compares the obtained application results against the expected ones to fulfil the use case requirements.
- **Section 6, Lessons Learned**, summarizes challenges and solutions in the evaluation process.
- **Section 7, Conclusions,** underlines the main outcomes of the technical evaluation.

In addition, the deliverable has an Appendix to provide the complete description of the test cases and their results in an exhaustive way. This is meant to complement the consolidated results in the main body of the document, allowing for an in depth look at details the reader might be interested in.

1.3. Intended audience

The dissemination level of D5.2 is public (PU) and is meant primarily for (a) all members of the 5G-MOBIX project consortium, and (b) the European Commission (EC) services. This document is intended to serve as a reference for the technical considerations in the 5G network when designing new solutions in CAM in cross-border environments.

2. EVALUATION METHODOLOGY

The evaluation methodology in 5G-MOBIX is the common tool to conduct the trials, acquire the data and evaluate the results on the 5G behaviour for CAM functions. It follows a V-model (Figure 1) that gathers all the processes involved in the technical evaluation, from the definition of the cross-border issues to the analysis of their impact on mobility, in three great blocks: preparation, trialling and evaluation.

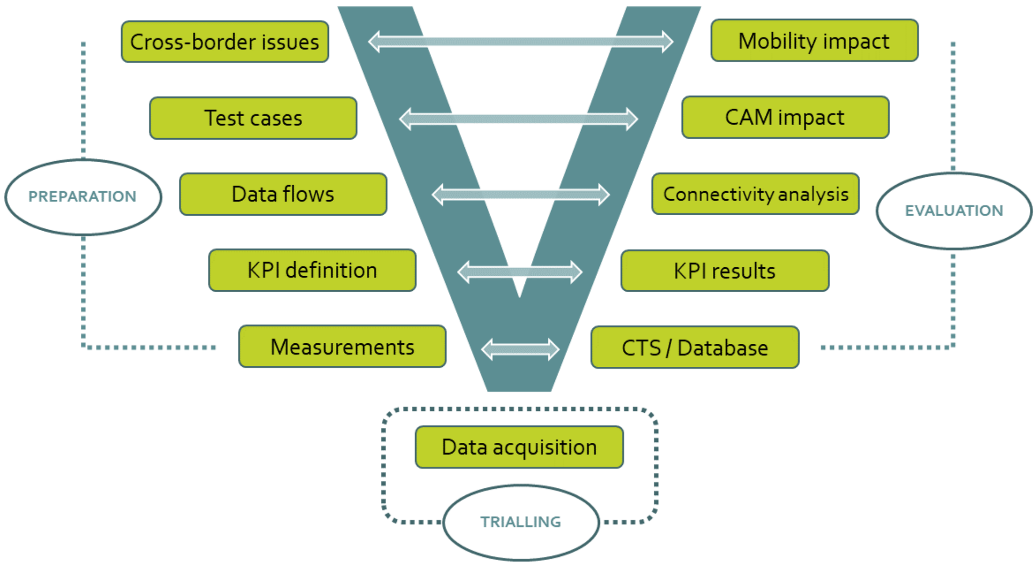


Figure 1: V-model in 5G-MOBIX

The design and implementation of the preparation and trialling activities are the result of multiple efforts along WP2 (Specifications), WP3 (Development, integration and roll out), WP4 (Trials) and WP5 (Evaluation) Tasks, showing strong dependencies all along the project. A brief description of these transversal activities is provided in this section with references to the corresponding deliverables with the information required.

The focus of this deliverable is on the right side of the V-model providing the insights on the technical evaluation, from the extraction of the KPI results for the connectivity analysis to the CAM and mobility impacts.

2.1. Cross-border issues and considered solutions

The overall assessment is centred around the cross-border issues (XBIs) that enumerate the various factors expected to impact on the delivery of timely, continuous and seamless provisioning of CAM services in cross-border environments. The final list of XBIs in 5G-MOBIX orients the deployment, trialling and evaluation activities towards the telecom and application issues. These activities focused on specific system configurations and/or deployment options, identified and described in the form of considered solutions (CSs) aimed to address the identified XBIs.

As presented in D3.7 [1], each XBI is associated with one or more CS that aim to address the issue at hand. As such, groups of comparable CSs have been identified, as presented in Tables 7 and 8 of D3.7 [1]. Table 1 provides a short view of this XBI and CS lists with some minor updates on the association of CS to XBIs.

Table 1: XBI and CS used for technical evaluation in 5G-MOBIX

XBI		Associated CS	
ID	**Name**	**ID**	**Name**
XBI_0	*Baseline*	*CS_0*	Feature OFF
XBI_1	NSA Roaming interruption	CS_1	S1 handover with S10 interface using an NSA network
		CS_2	Release and redirect using an NSA network
		CS_3	Release and redirect with S10 interface using an NSA network
XBI_2	SA Roaming interruption	CS_6	Release and redirect using an SA network
XBI_3	Inter-PLMN interconnection latency	CS_7	Internet-based Interconnection
		CS_8	Direct Interconnection
XBI_4	Low coverage Areas	CS_9	Satellite connectivity
XBI_5	Session & Service Continuity	CS_4	Multi-modem / multi-SIM connectivity - Passive Mode
		CS_5	Multi-modem / multi-SIM connectivity-Link Aggregation
		CS_10	MEC service discovery and migration using enhanced DNS support
		CS_11	Imminent HO detection & Proactive IP change alert
		CS_12	Inter-PLMN HO, AF make-before-break, SA
		CS_13	Double MQTT client
		CS_14	Inter-MEC exchange of data
		CS_15	Inter-server exchange of data
XBI_6	Data routing	CS_16	LBO NSA
		CS_17	HR NSA
		CS_18	LBO SA
		CS_19	HR SA

XBI_7	Insufficient Accuracy of GPS Positioning	CS_20	Compressed sensing positioning
XBI_8	Dynamic QoS Continuity	CS_21	Adaptive Video Streaming
		CS_22	Predictive QoS
XBI_9	Geo-Constrained Information Dissemination	CS_23	Uu geobroadcast
		CS_24	PC5 geobroacast
XBI_10	mmWave applicability	CS_25	mmWave 5G
XBI_11	Network slicing applicability	CS_26	Network slicing

The analysis of the considered solutions within each cross-border issue allows valuing the different options based on the development efforts and required improvements. In addition, the parallel analysis of different deployments with different use cases across the CBC/TS addresses the need of reproducibility of the results and their complementarity.

2.2. Test cases

Building around the identified cross-border issues and supported solutions, each CBC/TS defined a series of test cases to conduct the evaluation and drive the trials. Each test case is meant to ultimately assess/evaluate one or more cross-border issues and solutions. The project considers two groups of test cases for this mobility analysis:

- UCC/US agnostic test cases, defined in WP3, whose main aim is to validate the roaming and handover processes. These test cases form the basis for the network verification/validation process that follows the completion of a deployment activity. At the same time, however, these test cases support a network-level performance evaluation by using CAM-application agnostic synthetic traffic enabling the assessment of the baseline performance of the network in cross-border environments.

- UCC/US specific test cases, to assess the impact of the 5G mobility on the driving functions. These test cases are defined based on the operation of specific CAM applications reflecting a real-world application context. In these cases, network traffic is generated by the applications at hand. The objective is to enable the assessment of the impact of the various solutions/deployment options on the CAM application.

Both test case types have pursued the objective to get valuable data for the E2E system under evaluation. A detailed description of the test cases is provided in the Appendix.

2.3. Data flows

The main analysis on the test case data is performed at the traffic flow level by obtaining the connectivity parameters in the UCC/US agnostic test cases and the UCC/US specific ones. D5.1 [2] provided the definition of all considered UCC/US specific traffic flows, along with the corresponding mapping of KPIs i.e., which data plane KPIs will be measured on which traffic flows. All information is available in the Tables of D5.1 [2] Appendix C. For UCC/US-agnostic measurements, the exact traffic flows are defined by the synthetic traffic generation process.

2.4. KPI definition

The main source of evaluation data is obtained from the data flows at the 5G network level where two sets of KPIs have been defined: the general KPIs (TE-KPI1.x in Table 2) and the handover KPIs (TE-KPI2.x in Table 2), directly linked to the mobility processes. The initial definition of these KPIs is provided in D2.5 [3], updated in D5.1 [2] and reviewed in D3.7 [1] because it became evident that certain KPI definitions required revision and, in some cases, the introduction of more detailed KPI definitions was necessary. Table 2 summarizes the consolidated list of KPIs used for the technical evaluation.

Table 2: Technical KPIs in 5G-MOBIX

ID	Name	Description
TE-KPI1.1	User experienced data rate	Amount of application data (bits) correctly received within a certain time window (also known as goodput).
TE-KPI1.2	Throughput	Amount of data (bits) received per time unit.
TE-KPI1.3	E2E Latency	Elapsed time from the moment a message is transmitted by the source application to the moment it is received by the destination application instance(s).
TE-KPI1.3b	Latency	Elapsed time from the moment a data packet (network Protocol Data Unit) is transmitted by the source node, to the moment it is received by the destination node
TE-KPI1.4	Control plane Latency	Time to move from a battery efficient state (e.g., idle) to start of continuous data transfer (e.g., active).
TE-KPI1.5	User plane Latency	One-way time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface

		in either uplink (UL) or downlink (DL) in the network, assuming the mobile station is in the active state.
TE-KPI1.6	Reliability	Amount of application layer messages or network layer packets (subject to measurement level i.e., L2 or L1) successfully delivered to a given system node within the time constraint required by the targeted service, divided by the total number of sent messages or packets.
TE-KPI1.7	Position accuracy	Deviation between RTK-GPS location information and the measured position of a UE via 5G positioning services.
TE-KPI2.1	NG-RAN Handover Success Rate	Ratio of successfully completed handover events within the NR-RAN regardless if the handover was made due to bad coverage or any other reason
TE-KPI2.2	Application Level Handover Success Rate	Ratio of successfully completed application level handovers i.e., where service provisioning is correctly resumed/ continued past the network level handover, from the new application instance.
TE-KPI2.3	Mobility interruption time	Time duration during which a user terminal cannot exchange user plane packets with any base station (or other user terminal) during transitions. This is defined as the time difference between RRC Connection Reconfiguration and New Data Receive messages

These KPIs are the basis to assess CAM functions in cross-border environments by allowing a comparison of the measured KPI values against target KPI values identified based on the performance requirements of the applications at hand (where available). In practice, this translates to the identification of the KPI values required for the successful/smooth/unobstructed operation of the application, and their comparison against the actual values measured during the trials. A set of such values has been reported in D2.5 [3]. Section 5 revisits these values and provides a direct comparison against the actual KPI values measured during the trials.

2.5. Measurements

The project focuses its evaluation activities on capturing and analysing the performance delivered by the 5G networks towards the CAM applications. This translates to measurements targeting on the E2E performance, as well as finer grained measurements aimed to shed light on various aspects of the observed performance. This constitutes a set of different measurement facets which necessitate the differentiation of the exact KPIs and measurement mechanisms employed which is presented in the following:

A- E2E measurements

These measurements focus on the performance perceived by the user, and as such build on observations (logging of measurement data) at the application level of the communicating end points e.g., UE/OBU and application server. They are measured with TE-KPI1.1, TE-KPI1.3 and TE-KPI1.6.

B- Layered measurements

These measurements aim to: (i) capture the performance of the various protocol layers, through corresponding KPIs, and (ii) capture contextual information i.e., mainly radio conditions. The purpose is obviously to provide a better understanding of the impact of each layer to the overall, E2E performance observed. In order to simplify measurements, the project has identified the following three levels (described also in D5.1 [2]):

- **Level 0, Access:** above the access layer (LTE, 5G, etc.) defined in ETSI EN 302 665 [4]. Focuses on obtaining relevant information about the radio access network parameters (signal strength, cell identification, etc.). They are measured with TE-KPI2.1, TE-KPI2.2 and TE_KPI2.3.
- **Level 1, Transport:** above the transport level, specifically at the IP network/transport layer. Focuses mainly on obtaining relevant information about the capabilities of the network (throughput, delay, etc.), at its various segments i.e., not including the end points of communication. As such, it also allows distinguishing the network from higher layers (incl. Application) overheads. They are measured with TE-KPI1.2, TE-KPI1.3b, TE-KPI1.5 and TE-KPI1.6b.
- **Level 2, Application:** at the level where application data, such as ITS messages or video streams, are exchanged between end-points i.e., UE-UE, UE-Edge, UE-Cloud, the ITS stations or between an ITS station and the ITS control centre. Focuses on obtaining relevant measurement data at application level, such as E2E latency, user experienced data rate, reliability, etc. They are measured with TE-KPI1.1, TE-KPI1.3 and TE-KPI1.6.

C- Per network segment measurements

These measurements aim to capture (where possible) the performance of the network at its various segments, to assist in a better understanding of the contribution of each segment to the overall, E2E performance observed. They are measured with TE-KPI1.2, TE-KPI1.3b, TE-KPI1.5 and TE-KPI1.6. The network segments considered are:

- UE/OBU-gNB,
- gNB-PGW,
- PGW-MEC or PGW-CloudServer/ ITS control Centre.

D- On control vs. data plane measurements

The measurements aim to capture the impact of control plane performance on the E2E user perceived performance. This notably includes measurements related to the signalling for UE/network, as well as application state transitions during handover i.e., RRC connection establishment procedure, application level state transfer, etc. they are measured with TE-KPI1.4, TE-KPI1.7, TE-KPI2.1, TE-KPI2.2 and TE-KPI2.3.

2.6. Data acquisition

Data collection is applied on particular traffic flows, when it comes to the data plane KPIs. The remainder of the KPIs build on the collection of control plane raw data, regardless of the particular data traffic flows in place.

The project has specified the exact raw data required to be logged so that the selected KPIs can be subsequently calculated. The information to be collected includes mandatory parameters that should be provided by all trial sites, optional parameters that may be provided depending on the trial site needs and resources and some conditional parameters, which capture depends on specified conditions (e.g., some parameters are required by all use cases, but not required for application 'agnostic' test cases). The information is divided in different layers, as defined in D5.1 [2] and showed in D3.5 [5].

2.7. Central database

The next step refers to the handling of the raw data collected to enable the calculation of the KPIs. The project hosts a centralised test server (CTS) to collect and store the data from the CBC/TS in a central database and to allow the evaluators to browse access and download data.

Figure 2 presents an overview of the data input and processing flow. Once the local measurement data are translated into a common data format, there is a tool to check the data validity and sanity to avoid uploading corrupt data to the CTS file repository. On the second step, a script populates a relational database with all the test data and metadata, making everything available using a data schema equivalent to the common data format. This enabled programmatic access to the data, enabling direct data query and calculations of descriptive statistics (e.g., mean, min/max, standard deviation, etc.) on all applicable variables and uploading them to the CTS relational database.

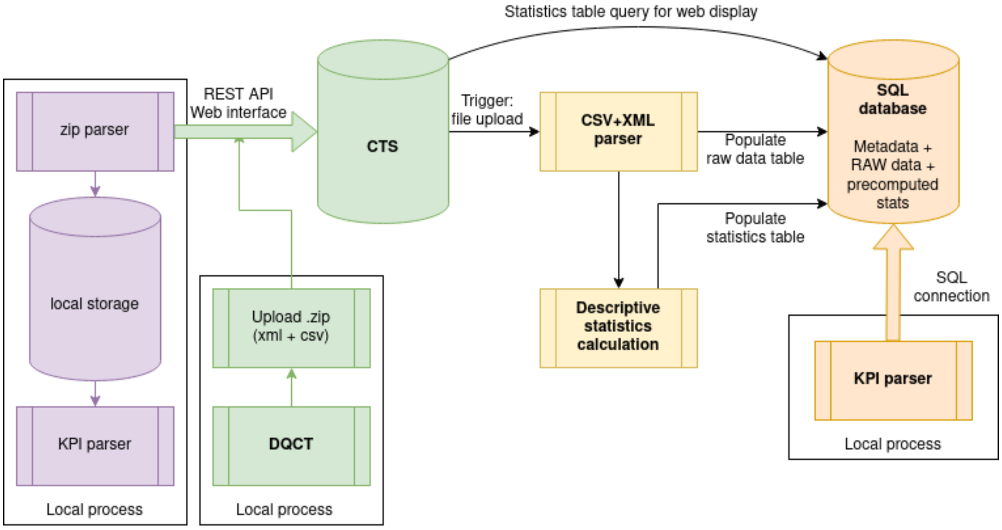


Figure 2: Data processing flow, CTS and central database

Each CBC/TS was free to use its own data management process to come up with the final calculation of KPIs at a local level or use this tool provided by the project. In this sense, the central database has a dedicated table with all the statistic results for all the test runs uploaded to the CTS that can be queried in a very agile way to obtain the evaluation results, validate the ones obtained at a local level or cross-check results across CBC/TS (Figure 3).

```
SELECT statistic.* FROM statistic, test_data_net_transp_aggr
WHERE test_data_net_transp_aggr.messagetype='ETSI\.CAM' AND test_data_net_transp_aggr.flowdirection='UL'
AND test_data_net_transp_aggr.communicationprofile='NR_NSA' AND test_data_net_transp_aggr.communicationprotocol='TCP'
AND statistic.variable='e2elatency'AND test_data_net_transp_aggr.id_test_file=statistic.id_test_file
GROUP BY statistic.id
```

id_test_file integer	samples integer	mean real	median real	maximum real	minimum real	std_dev real	quantile_25 real	quantile_75 real	confidence_interval_95 real	quantile_95 real
700	75	20.261568	20.21501	26.796103	14.405632	2.5733693	18.332947	22.171854	0.58240825	24.236813
704	46	14.484956	13.554939	30.376673	10.800171	4.1677175	11.948895	14.835352	1.2044129	23.830774
708	76	20.34674	20.423197	27.137089	13.901448	3.2041173	17.363714	23.02172	0.72037345	25.33068
712	85	16.86645	16.7207	24.714064	13.4094715	2.0338798	15.394115	17.809319	0.43238625	20.450172
722	102	15.374728	15.359855	22.280613	10.827923	2.2210014	13.683474	16.80184	0.43102732	19.155468
723	102	15.880841	15.641721	29.656887	12.560368	2.1328473	14.70362	16.578568	0.4139194	19.0823
725	102	19.161615	19.391167	24.475956	13.252576	2.3783026	17.45553	20.878971	0.46155462	22.654469

Figure 3: Example of central database functionality

3. CBC / TS EVALUATION OBJECTIVES

One of 5G-MOBIX's riches is the wide variety of 5G technologies used to support very different CAM functions along the CBC/TS. This is reflected in the different test cases ran under very different conditions: NSA or SA networks; HR and LBO roaming configurations or directly through satellite communications; network architectures with edge computing but also other with cloud solutions; vehicles and road infrastructures equipped with single-SIM OBUs and others with multi-SIM OBUs. All these options are captured by the corresponding CSs introduced earlier in the project, which drive the evaluation process as already mentioned (see Section 2.1) i.e., the main evaluation objective is assess these CSs, identifying potentially preferred technical approaches for addressing the associated XBIs.

This section highlights the evaluation objectives of each CBC/TS by explicitly outlining the list of XBI/CS in its scope. Each CBC/TS defined its own catalogue of test cases based on them. For instance, the main goals of both CBC were focused on testing the interruption times (XBI_1), inter-PLMN interconnection latencies (XBI_3), service continuity (XBI_5) and E2E latencies (XBI_6) as a result of the efforts in interconnecting their NSA networks in the two sides of their borders. This was investigated with the two different roaming options.

The Appendix of D5.2 provides a detailed characterization of each test case and D4.3 [6] the relationship between the XBI/CS and these test cases [5]. Both documents use the same identifiers for the test cases, that are also the ones that are going to be used in this document from now on: TCA-GEN-x for the generic set of UCC/US agnostic test cases, TCA-<CBC/TS>-x.y for the CBC/TS specific set of UCC/US agnostic test cases and <CBC/TS>-x.y for the UCC/US specific ones.

3.1. ES-PT CBC

The ES-PT CBC analysed the agnostic and the specific test cases deployed in the 5G NSA Option 3x networks provided by TELEFÓNICA (ES side) and NOS (PT side) and interconnected by NOKIA ES and NOKIA PT by means of the S1 handover using the S10 interface (CS_1). Most of the test cases were run under the HR roaming configuration (CS_17) and, at the last stage of the trialling phase, a selection of test cases was also run with LBO (CS_16). The design of the test cases has been oriented towards the correct understanding of the five cross-border issues addressed in ES-PT (XBI_1, XBI_3, XBI_5, XBI_6 and XBI_9) under different perspectives attending to: the driving direction, the SIM cards in the UEs or the network stressing.

The UCC/US agnostic test cases characterized the network capabilities in the cross-border locations, Old Bridge for the low-speed tests and New Bridge for the high-speed ones and they are the following: 1) TCA-

[5] The following subsections include for completeness all XBI/CS *and* corresponding TC identifiers. The latter are then summarized in Section 4 on a per XBI/CS basis to complement the reported results and provide the necessary index/link for more detailed information regarding the test case descriptions (D4.3) or results (Appendix).

ES-PT-02 to TCA-ES-PT-09 for general performance, roaming/handover processes and inter-MEC measurements; 2) TCA-GEN-12 to TCA-GEN-15 to measure the impact of the network stressing and 3) TCA-GEN-33 and TCA-GEN-34 to analyse the inter-PLMN latencies in the two roaming configurations.

The UCC/US specific test cases were executed firstly on the national side (ES and/or PT), to provide the baseline of the network behaviour, with the key tests being those conducted in the cross-border trials between ES and PT: Cooperative Automated and Remoted Driving in the Old Bridge and Overtaking, Lane Merge, HD-Maps and Public Transport Media in the New Bridge.

The test cases within the Advanced Driving UCC explore the advantages of the MEC in high demanding latency US. Overtaking tests were firstly executed on the ES side to check the exchange of ETSI messages through a broker hosted in the ES MEC (ES-PT-2.1) and then in the cross-border to analyse the inter MEC exchange of messages between the ES and PT MQTTs (ES-PT-2.2-ES-PT-2.6). The lane merge was also tested separately on the ES side (ES-PT-1.1), the PT side (ES-PT-1.10 and ES-PT-1.11) and the cross-border (ES-PT-1.2 and ES-PT-1.4) to study the effect of the presence of the RSUs in a manoeuvre. The cooperative automated was trialled in the cross-border to investigate the impact of the low speed (ES-PT-5.6 and ES-PT-5.7). All these tests were run with HR because the high service interruption times in LBO does not allow the performance of any autonomous function. Still, some tests with the data flows involved in the overtaking (but not the CAM function) were run in HR (ES-PT-2.10 and ES-PT-2.11) and LBO (ES-PT-2.12 to ES-PT-2.15) in order to perform direct comparisons on the performance measurements.

The HD-Maps US, belonging to Extended Sensors UCC, required the upload of a large file to a server behind the MEC. Tests in ES side (ES-PT-3.1) analysed the throughput capabilities and the ones in the cross-border with HR (ES-PT-3.2 and ES-PT-3.4) the inter-server implementation. In the framework of the collaboration of FI to the ES-PT CBC, HD-Maps was also tested under LBO to evaluate the service discovery (ES-PT-3.5).

The Remote Driving tests used a single instance of the remote crossing interface in the ES MEC to tests its execution on the ES side (ES-PT-6.1) and in the cross-border (ES-PT-6.3, ES-PT-6-6 and ES-PT-6.8).

The two use cases under the Vehicle QoS Support UCC and Media Public Transport US served to analyse the 4k streaming to a server behind the MEC (ES-PT-7.1) and the transfer of the multimedia content from a server in the internet (ES-PT-7.3) by using a MiFi device.

Many partners have been working actively on the evaluation activities enriching the results by using different UEs (single-SIM OBU by CTAG, single-SIM OBU by IT, multi-SIM OBU by ISEL, smartphone/PC by DEKRA or MiFi by ALSA), measurement tools (QLog tool by Qualcomm, TACS4 by DEKRA; QMICLI, Keysight, TCPDump, etc) and processing mechanisms, as it was described in D3.5 [5] and updated in D3.7 [1]. All these analyses have provided comparable results that validate the different approaches.

3.2. GR-TR CBC

Specific and agnostic tests at the TR and GR borders were conducted using the 5G NSA Option 3x network provided by TURKCELL (TR side) and COSMOTE (GR side). Antenna system, radio and core network equipment provided by ERICSSON TR and ERICSSON GR were used in the network infrastructure. Depending on the configuration of the tests for the low interruption handover between MNOs, S10 interconnection was used over the Internet (CS_7) or direct (leased line) (CS_8) connection. All tests were essentially performed according to HR - S10 over the internet (indirect) interconnection (CS_17, CS_7), HR - S10 over direct (leased line) interconnection (CS_17, CS_8), LBO - S10 over direct (leased line) interconnection configurations (CS_16, CS_8).

The aim was to ensure that the test cases of CAM services were to be made without any unforeseen network related problems. The tests were carried out on the bridge connecting the customs offices located at the TR and GR sides. During the agnostic tests, all possible configurations were checked using SIM cards and edge servers provided by TURKCELL and COSMOTE.

The design of the test cases was oriented towards the correct understanding of the cross-border issues addressed in GR-TR (XBI_1, XBI_3 and XBI_6) under different perspectives attending to: the driving direction, the SIM cards in the UEs or the network stressing.

5G Platooning US demands low latency communication between leader and follower vehicles and low interruption time while border crossing. To achieve these, partners used HR network configurations (CS_17), since LBO network configuration causes high interruption time (CS_16).

Similarly, the Assisted Zero-Touch Border Crossing US utilizes the detailed data provided by the CAM enabled truck's sensors (lidar, radar, GPS, etc.) as well as the data from surrounding heterogeneous information sources such as traffic cameras, road side sensors, smartphones, wearables. More, increased intelligence can be created based on a cooperative awareness of the borders' environment. Service continuity during the inter-PLMN handover is of utmost importance in such cases, and the existence of intelligent functionality deployed at the edge close to the border greatly facilitates continuous service. (CS_7 and CS_8).

3.3. DE TS

In the DE trial site, both UCC/US agnostic and specific test cases were conducted. TCA-DE-02 and TCA-DE-06 test cases have been performed, mostly to include important latency and reliability results. The results from these agnostic test cases are crucial in order to characterise and show the baseline performance of the two 5G networks that were used in the DE TS tests.

Regarding the UCC/US specific tests, five different test cases (DE-1.1 to DE-1.3 and D2.1 to DE-2.2) were defined and their results are reported. These test cases belong to the Platooning and Extended Sensors UCC. With the obtained results, the CAM application performance requirements have been verified and validated. Furthermore, they show which 5G communication technologies/interfaces (C-V2X PC5 (CS_24) vs 5G Uu (CS_23) are more adequate for the different applications and network flows tested in the DE TS (e.g., sensory data exchanged between vehicle and infrastructure or platooning messages exchanged between vehicles).

The design of the test cases has been oriented towards the correct understanding of the three cross-border issues addressed in DE (XBI_5, XBI_8 and XBI_9) under different perspectives relating to commercial network conditions, service continuity and service interruption.

3.4. FI TS

The main evaluation objectives for the FI TS have centred on two key solutions for the service continuity, namely, a multi-SIM OBU solution (CS_4, CS_5) and MEC service discovery and migration solution (CS_10). These solutions have been evaluated in the context of two user stories related to the Remote Driving and Extended Sensors UCC, as well as in UCC/US agnostic testing.

In the case of the multi-SIM OBU, the FI TS has been trialling the multi-SIM approach for addressing service continuity challenges (XBI-5) for V2N connectivity in any geographical location where connectivity to two (or more) PLMNs is possible through the use of a multi-SIM OBU solution. The multi-SIM solution has two modes, link selection mode (CS_4) and link aggregation (CS_5) mode, with separate evaluations and comparisons being conducted for each mode.

In link selection mode (CS_4), a multi-SIM OBU solution (based on mobile IP-tunnelling) with two SIM cards was utilized, whereby, the multi-SIM OBU device selected the 'best or high priority' 5G connection based on criteria including latency, signal strength and RAT priority. The trials with this multi-SIM OBU link selection solution were conducted in 5G NSA-mode within the Extended Sensors US (test cases FI-1.1, FI-1.2), Remote Driving US (test cases FI-3.1, FI-3.2) and in agnostic testing (TCA-FI-11). The latter agnostic testing was conducted in both FI TS and at the ES-PT CBC.

For the case of link aggregation mode (CS_5), the multi-SIM OBU device simultaneously utilized both 5G connections associated with each SIM card. The trials with this multi-SIM OBU link aggregation solution were conducted in 5G NSA-mode within the Remote Driving US (test cases FI-3.1, FI-3.2) and in agnostic testing (TCA-FI-12), both within the in FI TS environment.

In addition to the two multi-SIM modes described above, a benchmark scenario was trialled whereby the OBU has the multi-SIM features turned off (CS_0) and OBU is only operating with a single SIM card (rather than two SIM cards). The trials with this scenario were conducted in 5G NSA-mode within the Remote Driving US (test cases FI-6.1, FI-6.2) and in agnostic testing (TCA-FI-13).

In addition to the multi-SIM OBU solution, the FI TS trials and evaluations for a solution for service continuity in terms of MEC service discovery and migration is based on enhanced DNS support through association of

MEC with DNS edge servers for low latency applications (CS_10). This is motivated by scenarios whereby a vehicle's trajectory on the road/highway typically traverses serving areas of different cross MEC systems of different PLMNs both within nation's border and at cross-border areas. The trials with this MEC service discovery and migration solution were conducted in 5G NSA-mode within the Extended Sensors US (test cases FI-1.1, FI-1.2). Moreover, this solution is being trialled in ES-PT CBC for edge service discovery and migration for HD-Maps related US.

Finally, in addition to the two solutions evaluated above, a SA-SA LBO solution (CS_18) was briefly considered in the FI TS in the context of Extended Sensors US (test cases FI-2.1, FI-2.2) and Remote Driving US (test cases FI-4.1, FI-4.2). However, these trials were postponed due to unavailability of outdoor AALTO 5G SA networks within the required trialling time window.

3.5. FR TS

The FR TS has provided results for both UCC/US agnostic and UCC/US specific test cases. Regarding the UCC/US specific tests, four different test cases were defined, and their results are reported. In addition, fourteen agnostic tests cases have been performed. The main evaluation objectives for the FR TS have centred on three key solutions.

In the case of multi-SIM connectivity, the FR TS has been trialling the multi-SIM approach for addressing service continuity challenges (XBI_5). The multi-SIM solution has two modes, under passive mode (link selection) (CS_4) and with link aggregation mode (CS_5); with separate evaluations and comparisons being conducted for each mode in FR TS and ES-PT CBC ES-PT. (TCA-FR-.04, TCA-FR-05, TCA-FR-06, TCA-FR-07, TCA-FR-08 and TCA-FR-09). The trials with multi-SIM solutions were conducted in 5G NSA mode.

For the satellite solution (CS_9), the FR TS has been trialling the satcom approach for addressing service interruption in low coverage areas (XBI_4) in TCA-FR-12, TCA-FR-13 and FR-1.6.

In addition to the previous solutions, the FR TS tested and evaluated the applicability of 5G mmWave (XBI_10-CS_25). Different tests for the Advanced Driving with Assisted Infrastructure US have been performed. The trials with this scenario were conducted in 5G mode in agnostic testing (TCA-FR-01, TCA-FR-02, TCA-FR-10 and TCA-FR-11) and specific testing (FR-1.1, FR1.2 and FR1.3).

The design of the test cases has been oriented towards the correct understanding of the three cross-border issues addressed in FR (XBI_4, XBI_5 and XBI_10) under different perspectives attending to: the service continuity and service interruption.

3.6. NL TS

The main objectives for the NL TS are to test and evaluate the capabilities of 5G SA networks and to improve latency, reliability and roaming for CAM applications. The 5G NSA commercial network of KPN provides a baseline. Cross-border situations are created by two 5G SA test networks from KPN and TNO with gNB base stations about 1 km apart on the test route on the NL-A270 motorway and parking area. Developments and piloting concentrated on three technologies.

Slicing is used to improve the QoS of CAM data flows, especially in the presence of large background traffic flows (XBI_11). Different strategies for core and RAN slicing (CS-26), and prioritising slices are tested in cases NL-1-4 to NL-1-6 and NL-3.4 to demonstrate the potential effects of background traffic and solutions in section 4.11.

A local-breakout slicing setup is configured to facilitate a direct connection to the MQTT broker, hosted on a MEC node. Tests demonstrated the performance of core versus edge routing in test cases NL-1.1 to NL-1.3. To geo-constrain information dissemination and reduce data rates (XBI_9) MQTT brokers are used on MEC nodes (CS_23) and use quadtree topics to route local traffic. This is tested in test cases NL-1.3 to NL-1.11, NL-2.1 to NL-2.4, and NL-3.1 to NL-3.4. To continue services seamlessly between networks (XBI_5), the interconnection of the MECs through federation of MQTT brokers (CS_14) is deployed and tested in cases NL-1.7.

LBO roaming is tested with different release and redirect optimisation strategies in the UE (XBI_2, CS_6, test cases NL-1.8 to NL-1.11). These are compared to default roaming to demonstrate the improvements in interruption time and service continuity. The redirect functionality was not completely successful as explained in D3.7 [1] section 9. Although roaming interruption can be optimised significantly, it could not be made seamless and satisfy CAM requirements. Consequently, slice roaming could not be tested during this project period.

5G mmWave signals are tested to augment positioning of automated vehicles (XBI_7, CS_20) and tested in NL-3.5.

The focus has been on cross-border test cases for the Extended Sensors, Remote Driving and Advanced Driving UCC. The latter is also tested in cross-border scenarios in the ES-PT CBC. The full set of test cases NL-2.4, including single network scenarios, is listed in D4.3 [6] section 4.

3.7. CN TS

The main objectives for the CN TS are to evaluate the performance of the deployed SA network with service continuity (XBI_5). In the CN TS, both scenario-agnostic and specific test cases are carried out, and results are provided. The results from the agnostic test cases are crucial in order to characterize and show the main characteristics and performance of the dedicated 5G SA network that was used in the CN TS tests.

Nine site-specific test cases have been performed. These test cases belong to the Advanced Driving, Platooning and Remote Driving UCC. With the obtained results, the CAM application performance requirements have been verified and validated, mostly to include important data rate and latency results.

The testing cases have been performed using the networks of two commercial operators in the Jinan area: China Mobile and China Unicom. Both evaluate the performance of the deployed SA network in low coverage areas and service continuity (XBI-5). MNOs provide 5G NSA access in the areas where the tests have been conducted. The specific test cases used both MNOs to emulate a cross-border scenario while driving in the closed test route of Jinan.

The CN TS focused on the evaluation of multi-SIM / multi-modem solutions (CS_4 and CS_5) as well as different edge computing configurations (CS_13 and CS_14). In Advanced Driving, two test cases (CN-1.1 and CN-1.2) were performed as baseline tests and one test case (CN-1.3) was performed to evaluate the performance of the multi-modem solution with link mode (XBI5/CS_5) with the redundancy of edge service configuration (CS_14). In order to solve the roaming issues in low coverage areas, two test cases (CN-2.1 and CN-2.2) were performed as baseline tests and the test case multi-SIM solution with link selection mode (CN-2.3) was performed to evaluate the performance of CS_4. In order to improve service continuity in roaming scenario, two test cases (CN-3.1 and CN-3.2) were performed as baseline tests and one test case (CN-3.3) was performed to evaluate the performance of the multi-modem solution with link mode (XBI5/CS_5) with the redundancy of edge service configuration (CS_14).

The design of the test cases has been oriented towards the correct understanding of the cross-border issue addressed in CN (XBI_5) under different perspectives relating to commercial network conditions, service continuity and service interruption. The CN TS focused on the evaluation of multi-SIM / multi-modem solutions (CS_4, CS_5) as well as different edge computing configurations (CS_13 and CS_14).

3.8. KR TS

The main objectives for the KR TS are to demonstrate feasibility and capabilities of a mmWave-band (XBI_10, CS_25) vehicular communication system for providing two US, Tethering via Vehicle and Remote Driving. For the demonstrations of Tethering via Vehicle and Remote Driving, a mmWave-band 5G NR vehicular communication system has been developed and deployed at two different KR trial sites to verify whether the system meets the performance requirements of the two US.

The demonstration of Tethering via Vehicle was conducted at the end of November 2020 on a highway test track in Yeoju, KR. In this trial site, a mmWave OBU (vehicle UE) is installed on the demo bus, and network equipment including 5G core and five gNB DUs is deployed along the trackside. The main purpose of the demonstration is to show that all the functionalities of the developed system work as expected and the developed mmWave-band system is capable of providing broadband onboard Wi-Fi services to onboard passengers. It evaluates the performance of the developed mmWave systems (XBI_10, CS 25) in Tethering via Vehicle mmWave communication use case in terms of user-experienced data rate (uplink date rate measured in the physical layer) (KR-1.1), reliability (downlink packet loss) (KR-1.2), and user plane latency (KR-1.3).

The demonstration of Remote Driving was conducted in April 2022 on an autonomous vehicle proving ground located at KATECH premises in Cheonan-Si, South KR. In this trial site, one gNB and one mmWave OBU (vehicle UE) are installed on a movable van and a remote-control vehicle, respectively. The main purpose of the demonstration is to investigate whether the developed mmWave-band system has the potential to realize a Remote Driving application. It evaluates the performance of the developed mmWave systems (XBI_10, CS_25) in Remote Driving using mmWave communication use case in terms of user-experienced data rate (uplink date rate measured in the physical layer) (KR-2.1), reliability (downlink packet loss) (KR-2.2), and mobility interruption time (KR-2.3).

4. EVALUATION RESULTS

The aim of this section is to highlight the most significant results achieved in the deployment of CAM functions from the analysis of the data flows involved in their V2X communications. The results are presented on a per XBI basis, further then distinguishing the various associated CSs. XBI and CS definitions have been provided in D3.7 [1], Section 2.6. The Appendix provides a link to a finer grained representation of the results. As in previous section, it is provided all necessary test case identifiers hereafter to assist in locating the required information there.

4.1. XBI_1: NSA Roaming Interruption

Mobility interruption time in inter-PLMN environments is defined as the time duration a UE cannot transmit or receive user data. In HR roaming, this corresponds to the handover time from the source cell to the target cell and in LBO roaming it also considers the time to restore the IP network connection in the target PLMN (see also Section 4.6). Results about service interruption time are provided separately in XBI_5.

Commercial networks usually do not allow inter-PLMN handovers. When leaving a country, a UE will stay connected to the home network until it loses synchronization of the last cell which connected. For a long time, the quality of the radio link drops to very low levels, and the establishment of speech and the simplest data service is not allowed by the network. After losing synchronization, the UE starts searching for the appropriate cell in the visited country. It will then establish a new PDN connection usually resulting in a new IP address. When the UE attaches to the visited network, it will typically still use a PGW in its home network. This will be the same PGW as before the roaming process. The SGW in the visited network and the PGW in the home network communicate over the S8-interface. The MME in the visited network and the HSS in the home network communicate over the S6a interface. Interfaces S8 and S6a are realized over an IPX network. This could be either the public internet or direct connection. All above definitions addressing to the HR inter-PLMN handover configuration.

During 4G and 5G handover, communication is interrupted for a short time when the UE lets go of the source cell and is not yet synchronized to the target cell. In case of 5G NSA this refers to the 4G anchor cells, but another interruption can occur when adding the 5G cell as secondary cell in the target network.

NSA uses an LTE cell as anchor for the NR cell. In LTE, there are two basic RRC states: idle and connected. In idle state, there is no connection between the terminal and the eNB so the terminal is inactive from an application-level perspective. In this state, the terminal - i.e. the UE - performs periodic decoding of the system information broadcast by the network, decodes paging messages, and takes care of the cell reselection, i.e., makes sure it is always camped to the best cell, based on its own radio measurements. This process is called cell reselection. In the RRC connected state, there is an active connection between the UE and the network, through the eNB and can exchange both signalling and user data, plus the terminal location is known at the cell level. Terminal mobility is under the control of the network using the handover procedure, with decisions based on many possible criteria including measurement reported by the UE or the eNB. In NSA, the NR gNB is a secondary cell to the master LTE cell. Handover of the NR secondary cell, maintaining the master LTE cell can also take place based on measurements of the NR physical layer. Handover in LTE and 5G NR is of the type "hard" handover, which means the current radio link, the link to the source cell, must be broken before a new connection to the target cell is established, resulting in service interruption.

Handover has three main phases: preparation, execution and completion. The procedure normally starts with the source or serving eNB, receiving a *measurement report* triggered at the UE by a handover event (parameters configured by the network). The serving and the target eNB exchange messages to reserve resources in the target eNB. This is performed through an X2 interface, if it exists, otherwise the MME is involved. In this type of handover (intra LTE), the *RRC connection reconfiguration* message acts as a handover command, starting the execution phase. During this phase, data is forwarded from the source eNB to the target eNB, which buffers the packets. UE moves to idle state, then needs to synchronize to the target cell and perform a random access to enter into *RRC connected state* and to obtain UL allocation and timing advance as well as other necessary parameters. Finally, the UE sends a handover confirm (*RRC Configuration complete*) message to the target eNB after which the target eNB can start sending the forwarded data to the UE.

In the cross-border situation the handover is going to take place from one cell in the current country to a cell in a neighbour country. To achieve this, the current cell must configure the UE to report measurements in neighbour cells in its own country and cells in the neighbour country. Thus, a high level of coordination among operators in different countries is needed. Furthermore, handover across countries involves changing the MMEs and thus a tracking area update procedure is triggered after handover.

In terms of 5G (NSA), the 5G NR bearer is a secondary cell to the master LTE cell. During handover the UE moves from *RRC connected* state to *RRC idle* and then back to *RRC connected* in the target cell. When the UE moves from *RRC connected* to *RRC idle*, it releases the 5G secondary cell and, once it re-enters *RRC connected* state in the target cell, it gets a new 5GNR secondary cell allocation.

As already analysed in D3.7 [1] (section 3.1 to 3.3), there are various handover options (corresponding, in the context of our XBI/CS framework, to CS_1, CS_2 and CS_3). Finally, both CBCs have opted for the S1 handover with S10 interface using an NSA network (CS_1), which allows exploring the advantages of the most complete solution within the proposals and also obtaining comparable measurements to extrapolate reliable conclusions. XBI_1 has been analysed by the two CBCs (Table 3) collecting measurements at the radio layer to obtain: TE-KPI2.1 (NG-RAN handover success rate) and TE-KPI2.3 (handover time). ES-PT calculated these KPIs with information from the UE and GR-TR with data from the network.

Table 3: Summary of UCC/US where XBI_1 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_1: S1 handover with S10 interface using an NSA network	ES-PT	Agnostic Tests	NA	TCA-GEN-33
		Advanced Driving	Lane Merge	ES-PT-1.2 and ES-PT-1.4
			Overtaking	ES-PT-2.2 to ES-PT-2.6
			Cooperative Automated	ES-PT-5.6 and ES-PT-5.7
		Extended Sensors	HD-Maps Vehicle	ES-PT-3.2 and ES-PT-3.4
	GR-TR	Agnostic	NA	TCA-GR-TR-06 and TCA-GR-TR-07

4.1.1. CS1: S1 handover with S10 interface using an NSA network

ES-PT CBC

The handover at the ES-PT cross-border involves PLMNs from two countries: TELEFÓNICA (ES) and NOS (PT). To estimate the handover interruption time, the radio interface (Uu) messages and internal status messages logged by the chipset have been used. The initial time for triggering the execution of the handover is the *RRC Connection Reconfiguration* message sent on the downlink dedicated control channel (DL_DCCH) of the serving cell. In Figure 4 (note that some messages have been filtered), NOS is operating in EARFCN=3150 and the physical cell id is 105. The message is sent shortly after a *Measurement Report* (send on the uplink dedicated control channel UL_DCCH). The UE responds with *RRC Connection Reconfiguration Complete* in the uplink dedicated control channel (UD_DCCH) of the target eNB. TELEFÓNICA is operating in EARFCN=2850 and the target physical cell id is 11. In the target cell, a *Tracking Area Update* procedure is triggered by the UE (in the UL dedicated control channel, UL_DCCH), accepted by the network (in the downlink dedicated control channel, DL_DCCH), and confirmed or completed by the UE (in the uplink dedicated control channel, UL_DCCH). The arrival time of the internal message *LTE MAC DL Transport Block* immediately after completing the *Tracking* procedure is taken as the time when the service interruption finishes.

As already mentioned, because of the transitions from *RRC connected* to idle, and then back to *connected*, in the target cell, the 5G secondary cell is released. The release takes place in the preparation phase, even before the *RRC Reconfiguration* message associated with the start of the handover procedure is received.

Once the UE is in the target cell and sends *Measurement Reports* messages, the target eNB initiates the process of adding the secondary 5G NR cell. Figure 4 shows the relevant messages. The UE is connected to a serving cell with LTE physical cell id 105 in PT, and with a secondary 5G cell which operates in the frequency 3620,64 MHz (NRARFCN = 641376) and also has physical cell id 105. After the handover and switch to the network in ES, the 5G secondary cell is added, in the frequency 3774,72 MHz (NRARFCN = 651648) and with physical cell id 168. Note that 5G is in TDD mode and LTE in FDD mode which may be subject to synchronization issues in the early stages of the technology.

Second	Description	Message Type	LTE PCI	LTE ARF	Additional Info	NR ARF	NR PCI
45,44	LTE RRC OTA Packet	UL_DCCH / MeasurementReport	105	3150			
45,575	NR5G ML1 Searcher Measurement Database Update Ext					641376	105
45,671	NR5G RRC OTA Packet	RADIO_BEARER_CONFIG				641376	105
45,675	LTE RRC OTA Packet	DL_DCCH / RRCConnectionReconfiguration	105	3150	handoverType intraLTE		
45,717	LTE RRC OTA Packet	UL_DCCH / RRCConnectionReconfigurationComplet	11	2850			
45,741	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformationBlockType1	11	2850			
45,741	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation	11	2850			
45,741	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation	11	2850			
45,741	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation	11	2850			
45,741	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation	11	2850			
45,749	LTE RRC OTA Packet	DL_DCCH / RRCConnectionReconfiguration	11	2850	measConfig		
45,753	LTE NAS EMM Plain OTA Outgoing Message	Tracking area update request Msg					
45,758	LTE RRC OTA Packet	UL_DCCH / RRCConnectionReconfigurationComplet	11	2850			
45,815	NR5G ML1 Searcher Measurement Database Update Ext					651648	
45,88	NR5G ML1 Searcher Measurement Database Update Ext					651648	
45,901	LTE RRC OTA Packet	DL_DCCH / DLInformationTransfer	11	2850			
45,901	LTE NAS EMM Plain OTA Incoming Message	Tracking area update accept Msg					
45,902	LTE NAS EMM Plain OTA Outgoing Message	Tracking area update complete Msg					
45,934	LTE RRC OTA Packet	DL_DCCH / DLInformationTransfer	11	2850			
45,934	LTE NAS EMM Plain OTA Incoming Message	EMM information Msg					
45,96	NR5G ML1 Searcher Measurement Database Update Ext					651648	
46,04	NR5G ML1 Searcher Measurement Database Update Ext					651648	
46,12	NR5G ML1 Searcher Measurement Database Update Ext					651648	
46,16	LTE RRC OTA Packet	UL_DCCH / MeasurementReport	11	2850			
46,2	NR5G ML1 Searcher Measurement Database Update Ext					651648	
46,201	LTE RRC OTA Packet	UL_DCCH / MeasurementReport	11	2850			
46,24	LTE RRC OTA Packet	UL_DCCH / MeasurementReport	11	2850			
46,248	LTE RRC OTA Packet	DL_DCCH / RRCConnectionReconfiguration	11	2850			
46,28	NR5G ML1 Searcher Measurement Database Update Ext					651648	
46,283	LTE RRC OTA Packet	UL_DCCH / RRCConnectionReconfigurationComplet	11	2850			
46,36	NR5G ML1 Searcher Measurement Database Update Ext					651648	
46,368	LTE RRC OTA Packet	DL_DCCH / RRCConnectionReconfiguration	11	2850	measConfig		
46,369	NR5G RRC OTA Packet	RRC_RECONFIG				641376	105
46,369	NR5G RRC OTA Packet	RADIO_BEARER_CONFIG				641376	105
46,385	NR5G RRC OTA Packet	RRC_RECONFIG_COMPLETE				651648	168
46,386	LTE RRC OTA Packet	UL_DCCH / RRCConnectionReconfigurationComplet	11	2850			
46,42	NR5G ML1 Searcher Measurement Database Update Ext					651648	168
46,434	NR5G MAC RACH Trigger						
46,594	NR5G ML1 Searcher Measurement Database Update Ext					651648	168

Figure 4: ES-PT CBC, sequence of signalling messages involved in the handover process

The LTE mobility interruption time (radio handover time) is calculated as the time between the *RRC Connection Reconfiguration* message and the first DL message received from the destination network (marked in yellow in Figure 4, 42 ms in the example).The NR mobility interruption time (green lines in Figure 4) goes from the *RRC Connection Reconfiguration* message received by the UE to the *LTE MAC DL Transport Block* message after the *Tracking* procedures (234 ms in the example). However, recovering full 5G connectivity in the new network took 919 ms (purple messages in Figure 4).

ES-PT has carried out tests to obtain the handover time when: 1) crossing from home to visited network and from visited to home network, 2) driving at low speed in the Old Bridge and at high speed in the New Bridge and 3) without and with network stressing. Network stressing is artificially created through two vehicles (one stopped on the ES side and another on the PT side) generating UL/DL traffic.

Table 4 shows the handover time obtained by using synthetic traffic in TCP protocol in a test driving from PT to ES (TCA-GEN-33). It is appreciated a small difference in the time required to complete the handover when returning to the home network compared to when performing the handover to a visited network. This is probably due to the fact to the reduced signalling required when returning to the user home network.

Table 4: ES-PT CBC, handover time (TE-KPI2.3) for TCA-GEN-33

Driving direction	samples	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI 95%	Perc. 95
From PT to ES with ES SIM	32	243,44	248	49,29	279	156	17,08	276,90
From ES to PT with ES SIM	18	337,56	338	79,68	369	300	36,81	363,90

Very similar results were obtained for the specific test cases. Figure 5 shows the handover success rate (TE-KPI-2.1) for Overtaking (New Bridge at high speed, ES-PT-2.2 and ES-PT-2.4 without network stressing and ES-PT 2.3 and ES-PT-2.5 for stressed tests) and Cooperative Automated (Old Bridge at low speed, ES-PT-5.6 without network stressing and ES-PT-5.7 for stressed tests) test cases driving from PT to ES with all the modems carrying the ES SIM. Figure 5 discriminates the number of handovers correctly executed, meaning with the logs according to Figure 4, and the tests where the modem has not performed the change of PLMN in the framework of the manoeuvre, maintaining the connectivity with the source PLMN.

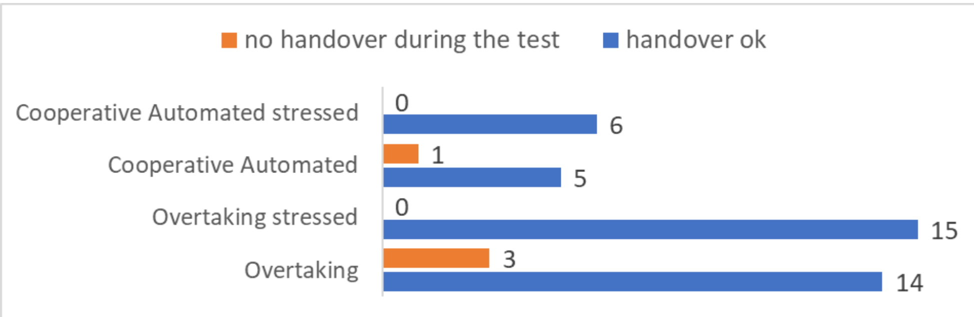


Figure 5: ES-PT CBC, ratio of successful handovers

For the successful handovers in Figure 5, Table 5 shows the average value of the handover time (both in LTE and NR) denoting again comparable results according to the vehicle speed or network stressing.

Table 5: ES-PT CBC, handover times in LTE and NR for Overtaking and Cooperative Automated tests

Test Case	RA	samples	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI 95%	Perc. 95%
Overtaking	LTE	12	39	36	9	68	35	33.1-45.0	36
	NR		245	241	20	280	215	232-258	277
Overtaking stressed	LTE	14	39	39	16	72	13	29.8-47.7	39
	NR		233	227	21	272	196	221-245	271
Cooperative Automated	LTE	6	33	36	8	37	16	23.9-41.1	36
	NR		229	231	6	236	219	221-237	235

Cooperative Automated stressed	LTE	4	35	36	1	36	33	32.7-37.2	36
	NR		236	232	12	252	223	199-273	250

The LBO roaming configuration, in addition to this handover time, requires the setup of a new data session by means of a detach/attach process performed by the modem of the OBU. The trigger to the new data session comes from the UE side because this functionality is not yet available from the network side. Figure 6 depicts the signalling messages in this process. Once the modem detects a PLMN change in the broadcast channel (BCCH) it triggers a *Detach request Msg* from the network, followed by an *Attach request Msg* to obtain a new IP address.

Second	Code	Message	Description	Message Type
31.111	[EC]	0xB063	LTE MAC DL Transport Block	
31.134	[FA]	0xB0C0	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation
31.139	[BE]	0xB0C0	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformationBlockType
31.144	[8B]	0xB0C0	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation
31.161	[68]	0xB063	LTE MAC DL Transport Block	
31.211	[BA]	0xB063	LTE MAC DL Transport Block	
31.237	[14]	0xB0ED	LTE NAS EMM Plain OTA Outgoing Message	Detach request Msg
31.238	[D3]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / ULInformationTransfer
31.261	[8F]	0xB063	LTE MAC DL Transport Block	
31.311	[E7]	0xB063	LTE MAC DL Transport Block	
32.279	[8B]	0xB0C0	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformationBlockType
32.414	[D1]	0xB0C0	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation
32.428	[39]	0xB0C0	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation
32.444	[D3]	0xB0C0	LTE RRC OTA Packet	BCCH_DL_SCH / SystemInformation
32.447	[42]	0xB0ED	LTE NAS EMM Plain OTA Outgoing Message	Attach request Msg
32.448	[48]	0xB0C0	LTE RRC OTA Packet	UL_CCCH / RRCConnectionRequest
32.535	[27]	0xB0C0	LTE RRC OTA Packet	DL_CCCH / RRCConnectionSetup
32.54	[4A]	0xB063	LTE MAC DL Transport Block	
32.541	[E9]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / RRCConnectionSetupComplete
32.569	[7D]	0xB0C0	LTE RRC OTA Packet	DL_DCCH / DLInformationTransfer
32.57	[79]	0xB0ED	LTE NAS EMM Plain OTA Outgoing Message	Identity response Msg
32.57	[27]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / ULInformationTransfer
32.59	[5E]	0xB063	LTE MAC DL Transport Block	
32.592	[93]	0xB0C0	LTE RRC OTA Packet	DL_DCCH / DLInformationTransfer
32.593	[04]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / ULInformationTransfer
32.64	[B6]	0xB063	LTE MAC DL Transport Block	
32.749	[EE]	0xB0C0	LTE RRC OTA Packet	DL_DCCH / SecurityModeCommand
32.75	[33]	0xB063	LTE MAC DL Transport Block	
32.75	[B6]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / SecurityModeComplete
32.75	[CD]	0xB0C0	LTE RRC OTA Packet	DL_DCCH / UECapabilityEnquiry
32.756	[87]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / UECapabilityInformation
32.775	[46]	0xB0C0	LTE RRC OTA Packet	DL_DCCH / RRCConnectionReconfiguration
32.788	[81]	0xB063	LTE MAC DL Transport Block	
32.797	[B2]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / RRCConnectionReconfigurationCc
32.808	[BC]	0xB0C0	LTE RRC OTA Packet	DL_DCCH / UEInformationRequest-r9
32.808	[FC]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / UEInformationResponse-r9
32.833	[02]	0xB0ED	LTE NAS EMM Plain OTA Outgoing Message	Attach complete Msg
32.833	[D3]	0xB0C0	LTE RRC OTA Packet	UL_DCCH / ULInformationTransfer
32.836	[C5]	0xB063	LTE MAC DL Transport Block	

Figure 6: ES-PT CBC, sequence of signaling messages involved in the IP change in LBO

Figure 7 shows the time to complete the detach/attach procedures in the New Bridge driving from ES to PT and PT to ES with TELEFÓNICA and NOS SIMs in a set of test cases with 6 test runs each. This time has to be added to the handover time to reflect the complete interruption time. The difference in the results is highly dependent on the number of antennas in the LOS of the vehicle when performing the handover but, in any case, these high interruption times make impossible the execution of any autonomous functions.

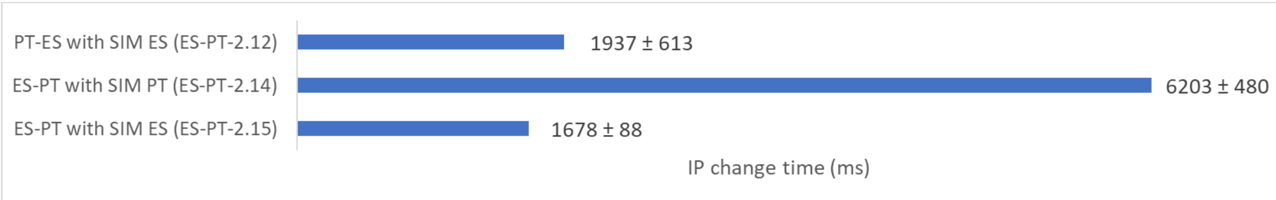


Figure 7: ES-PT CBC, time to perform the IP change after the handover in LBO

GR-TR CBC

NSA 5G, handover is mostly controlled and executed on the 4G eNodeBs (eNBs). The source eNB initiates a handover by sending *Handover Required* message over the S1-interface to its MME. The MME realises that the target eNB is not connected to it but to a different MME and that it has an S10-interface to that MME. It forwards the *Handover Required* message to the target MME through the S10-interface. From there, it reaches the target eNB which can decide if it accepts the handover request and if so handover confirms. Complete signalling flow illustrated in Figure 8 and mentioned messages can be followed through this diagram.

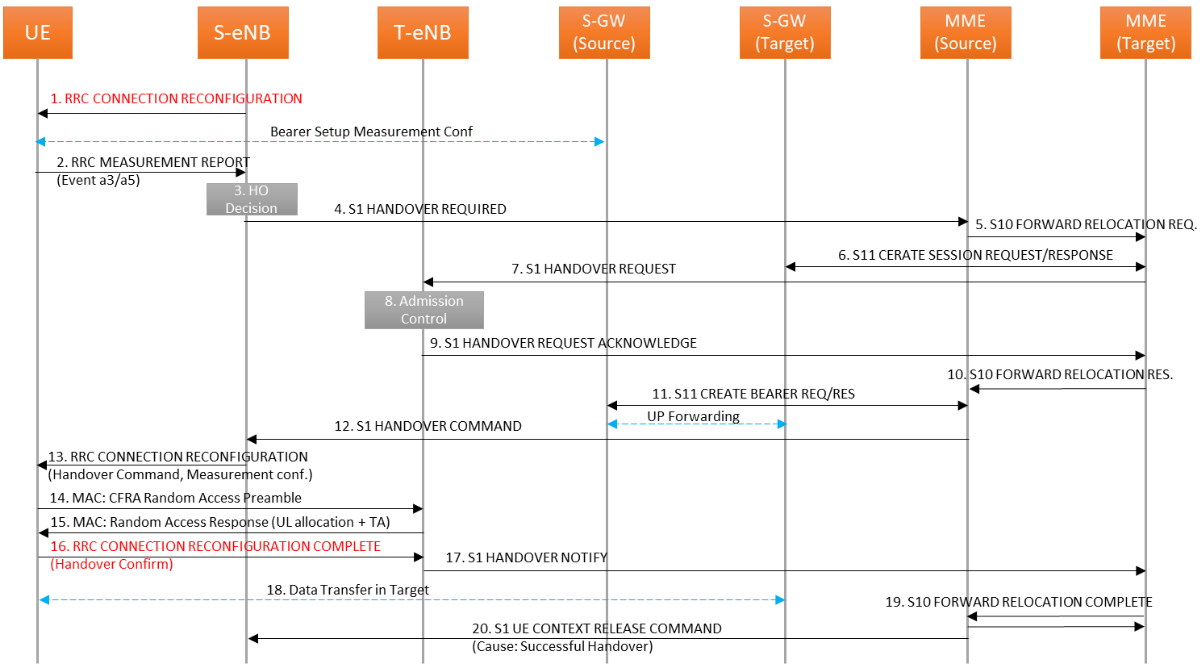


Figure 8: GR-TR CBC, inter-PLMN S1 handover signaling flow

In the GR-TR CBC, the LTE interruption time was calculated as the time difference between *RRCConnectionReconfiguration* message sent by source eNB to UE and *RRCConnectionReconfigurationComplete* message sent by UE to target eNB.

As it is known, control plane signalling in NSA Option 3x networks is carried over LTE network. The handover between the two networks is triggered by the LTE network with the measurements made by the UE. Meanwhile, the LTE and NR user data aggregated on the PDCP level are interrupted. After completion of LTE handover, user data starts flowing again over the LTE network. As the secondary gNB (SgNB) leg has not been added yet, the interruption on the 5G network continues. With the addition of SgNB, user data is aggregated at the PDCP level and 5G network starts to be used again. New Radio (NR) interruption was calculated as the time difference between *SgnbReleaseRequestAcknowledge* message sent by SgNB to MeNB and *E-RABModificationConfirm* message sent by MME to MeNB.

For the tests, a commercial smartphone and industry standard drive testing tool were used. Mobility interruption time was measured from TR to GR and from GR to TR. Table 6 contains information of the sample user data interruption during LTE handover process. In this example, LTE user data interrupted 56 ms for TR to GR and 57 ms for GR to TR. Similarly, Table 7 contains information of the sample user data interruption during SgNB leg removal and addition process. During that period, NR leg cannot be use for data downloading or uploading. In this example NR user plane data interrupted 224 ms for TR to GR and 177 ms for GR to TR.

Table 6: GR-TR CBC, LTE mobility interruption time

Longitude	Latitude	DateTime	LTE HoPdcpDlStopTime_TCA-GR-TR-04_INTERPLMN_HO_HR_TCP_DL_TEST1	LTE HoPdcpDlContinueTime_TCA-GR-TR-04_INTERPLMN_HO_HR_TCP_DL_TEST1		Interruption time	
26.31976937	40.94075450	2021-12-25 13:43:33.035	LTE HoPdcpDlStopTime		.		
26.31976937	40.94075450	2021-12-25 13:43:33.091		LTE HoPdcpDlContinueTime	.	56	TR->GR
26.32422143	40.93663173	2021-12-25 13:48:27.719	LTE HoPdcpDlStopTime		.		
26.32422143	40.93663173	2021-12-25 13:48:27.776		LTE HoPdcpDlContinueTime	.	57	GR->TR

Table 7: GR-TR CBC, NR mobility interruption time

Longitude	Latitude	DateTime	NR User Plane HO Start_TCA-GR-TR-04_INTERPLMN_HO_HR_TCP_DL_TEST1	NR User Plane HO End_TCA-GR-TR-04_INTERPLMN_HO_HR_TCP_DL_TEST1			
26.31976937	40.94075450	2021-12-25 13:43:33.035	NR User Plane HO Start		.		
26.31976937	40.94075450	2021-12-25 13:43:33.259		NR User Plane HO End	.	224	TR->GR
26.32422143	40.93663173	2021-12-25 13:48:27.719	NR User Plane HO Start		.		
26.32422143	40.93663173	2021-12-25 13:48:27.896		NR User Plane HO End	.	177	GR->TR

Figure 9 and Figure 10 below shows the variation of mobility interruption time in different inter network connections. In the left side of the both graphs giving the result of agnostic test case TCA-GR-TR06_InterPLMN_HO HR scenario that internet based inter connection has used. In the right side of the both graphs giving the result of agnostic test case TCA-GR-TR07_InterPLMN_HO HR scenario that direct (leased line) inter connection has been used. The core network configured as HR (CS_17) and S1 handover with S10 interface using an NSA network (CS3) for both scenarios. Synthetic TCP upload and TCP download traffic has generated by testing tool during tests.

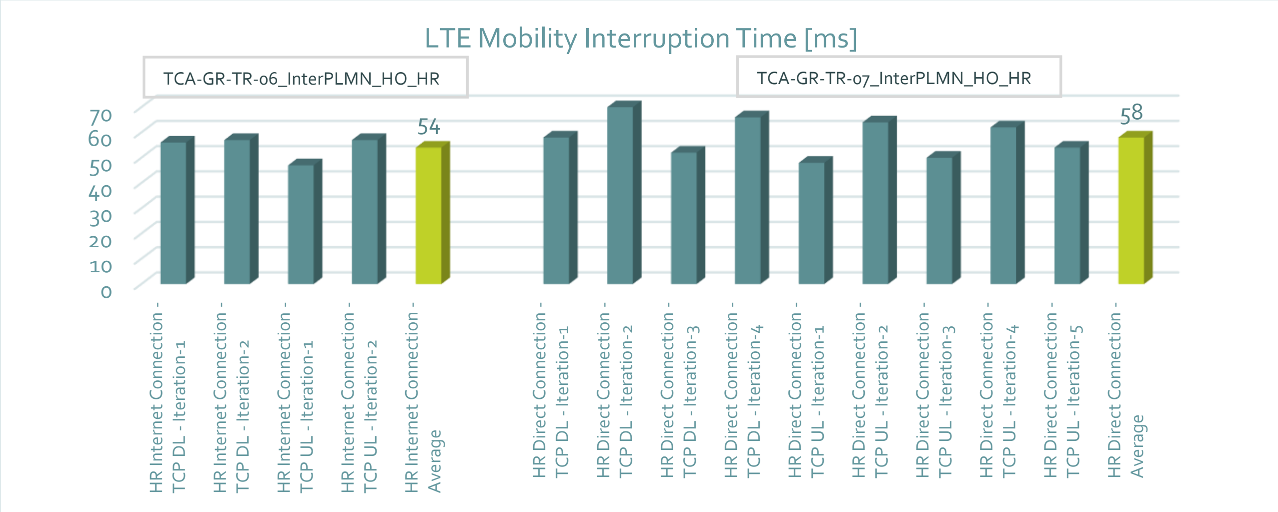


Figure 9: GR-TR CBC, LTE mobility interruption time in different trials

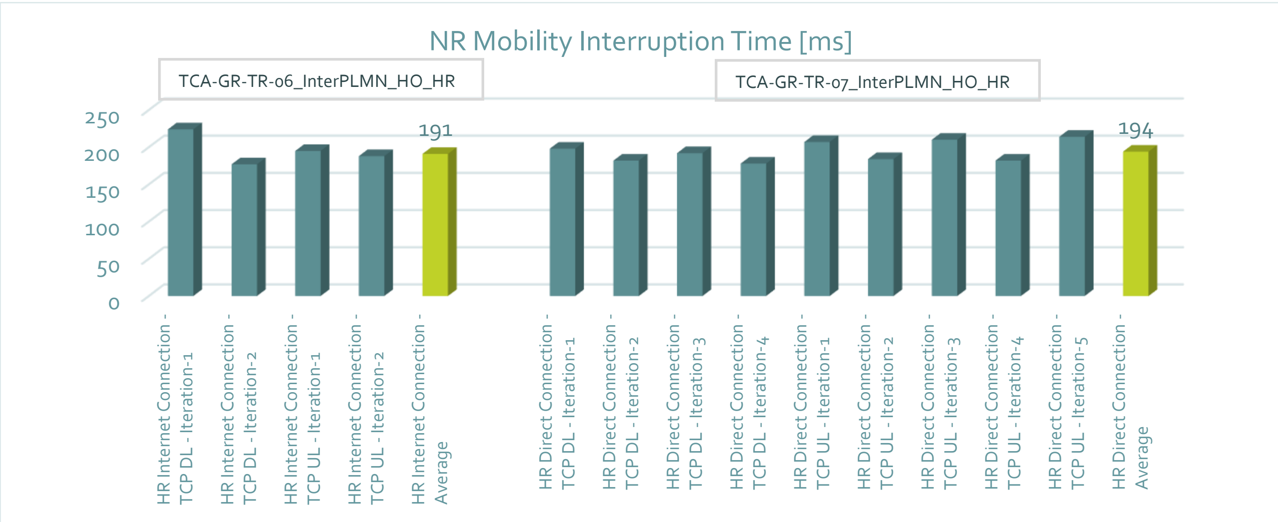


Figure 10: GR-TR CBC, NR mobility interruption time in different trials

Table 8 contains the test results of both scenarios. The results show that it makes no significant difference which lines are used to interconnect the PLMNs. The reason is that the S10-interface (using for two core network interconnection) is only used to prepare and initiate the handover. Delays on that interface only change the point where the handover happens, but not the interruption duration. Handover interruptions times, as a result of detaching from the source 4G eNB and synchronizing and attaching to the target one takes 58 ms and 54 ms for leased and public internet lines, respectively. The difference is within statistical uncertainty, as shown by the confidence intervals. It can therefore be concluded that the interruption time is identical for leased and public internet lines. They can be considered about the same according to the 95% confidence intervals. The 5G reconfiguration requires around 195 ms independent of network interconnection type, as this reconfiguration is only performed in the target (visited) network.

Table 8: GR-TR CBC, network interconnections change and interruption time (in ms) effect

Test Case	RA	samples	avg	median	stdv	max	min	CI 95%	Perc. 95
TCA-GR-TR-06_InterPLMN_HO_HR (Internet Based Inter Connection)	LTE	4	54	57	5	57	47	[47,62]	57
	NR	4	196	191	20	224	177	[164,227]	219
TCA-GR-TR-07_InterPLMN_HO_HR (Direct Inter Connection)	LTE	9	58	58	7	70	48	[52,64]	68
	NR	9	194	192	13	214	178	[183,204]	212

We have furthermore showed that seamless 5G Inter-PLMN handover is possible across country borders. Experienced interruption times of 50 ms should not have noticeable impact on CAM services. No interruption time issues were reported during the US tests.

LBO roaming can be enabled through configuration in the MME and PGW. In this case, the PGW selection algorithm in the MME would pick a PGW in the visited PLMN when a roaming UE wants to establish a PDN connection. In case of radio handover, including inter-PLMN handover, the PGW is never changed. A UE being handed over from its home PLMN to a visited PLMN will continue using the PGW of the Home PLMN. The E2E latency of user plane data between the client and server is still equally to the delays experienced in the HR scenario, since still the source PGW is used.

In order to reach LBO roaming after inter-PLMN handover, the PDN connection needs to be disconnected and reconnected, and this is a service interruption with potentially negative impact on use cases that needs to be accounted. This can be achieved in two ways. It is either triggered by the UE (similar to session and service continuity (SSC) mode 1 in 5G SA) or by the network (similar to SSC mode 2 in 5G SA), coming from the MME. This procedure is though not standardized in 5G NSA and thus both UEs and core network lack this capability. UE customization is required, or manual intervention needed. For the GR-TR CBC manual intervention (set UE to flight mode and then back to data) was used as the only technically available alternative, meaning that devices had to be disconnected and reconnected manually to get to LBO Routed Roaming after an Inter-PLMN handover.

Below is information about the procedure and results of an ICMP ping test to demonstrate that the LBO function is working. During the test, the interconnection between the networks was provided via the direct inter connection (leased line). The results of the test are shown in Figure 11.

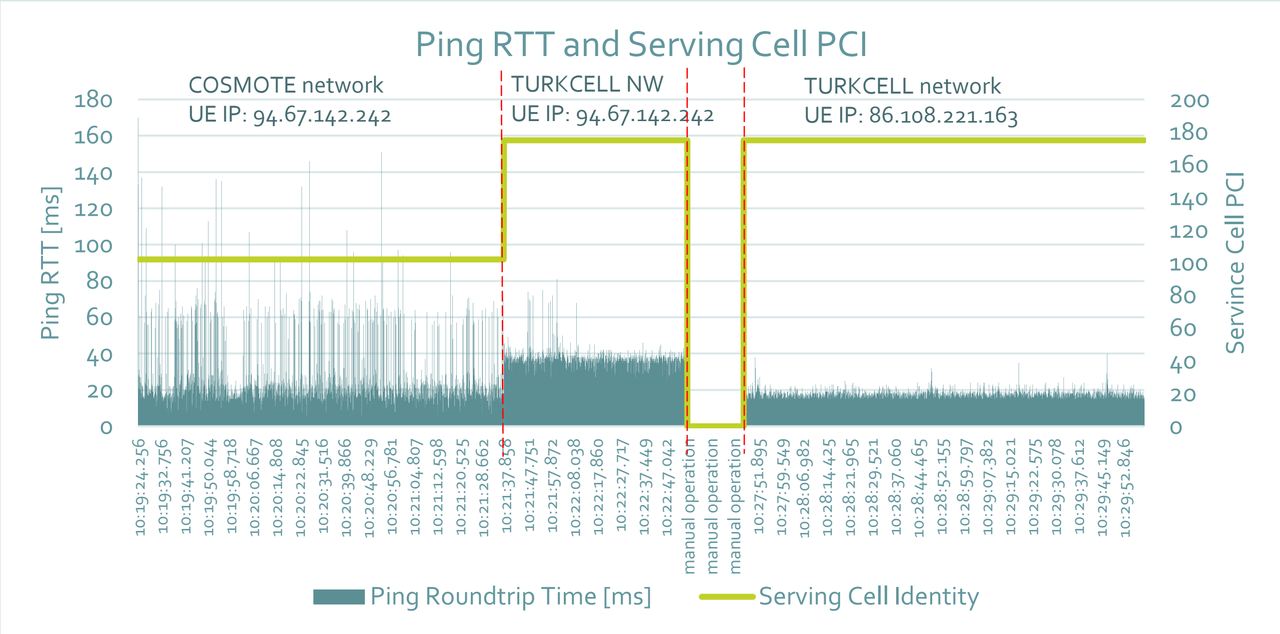


Figure 11: GR-TR CBC, ping RTT performance on LBO configured network

Given an example in Figure 11 COSMOTE SIM card, COSMOTE network and COSMOTE EDGE server were used at the beginning of the test. Before starting tests, it was checked whether the UE received the correct IP from the home network or not. In this example UE get 94.67.142.242 IP which is provided by home COSMOTE PGW.

While the user is in COSMOTE network, the ping data reached COSMOTE server by following the path: *UE -> COSMOTE RAN -> COSMOTE SGW -> COSMOTE PGW -> COSMOTE EDGE Server*. While the UE is using this path, the average E2E latency is around 23 ms.

When UE perform HO to Visited TURKCELL network ping data will follow below path: *UE -> TURKCELL RAN -> TURKCELL SGW -> Leased Line -> COSMOTE PGW -> COSMOTE EDGE Server*. While the UE is using this path, the average E2E latency value is around 38 ms. UE remain home network IP address. In this example UE sill getting service over 94.67.142.242 IP which is provided by COSMOTE PGW.

After flight mode on/off cycle UE takes new IP form visited network. In this example, UE TURKCELL received the IP number 86.108.221.163 issued by PGW. Also, before continuing, the test server needs to change manually. Because of test application (TEMS investigation) does not support such activity. After these activities ping data will follow the path: *UE -> TURKCELL RAN -> TURKCELL SGW -> TURKCELL PGW -> TURKCELL EDGE server*. This is similar path where UE on home network where roaming. While the UE is using this path, the average E2E latency value is around 17 ms.

Enabling LBO routed roaming, the average RTT is around 17 ms and its close to home and visited PLMNs. The use of the LBO configuration will be a significant advantage in applications requiring low latency. With this solution, leased line costs between operators can be reduced.

Within these trials the transition from HR roaming to LBO roaming was done manually by disconnecting and connecting the end-devices after inter-PLMN handover. For the future, we would like to demonstrate an automated transition to LBO roaming. We would furthermore like to demonstrate it in conjunction with SSC mode 3, enabling uninterrupted transition from HR to LBO.

4.1.2. Conclusions

Both CBCs have implemented the most complete solution (CS_1) for the optimization of the handover times by means of the direct interconnection of the MME's through the S10 interface. The measurement method used to estimate it was slightly different because of the different points of observation: ES-PT used drive testing with radio interface logging capabilities provided by the chipset and GR-TR logged at the MME-eNB interface.

The mobility interruption time in a default HR setup is about 200 -300 ms in ES-PT and GR-TR. Results showed that the LTE handover disruption amounts to the range of 40-50 ms, while the 5G NR leg adds another 200-250 ms. In total, these are considered as acceptable values for a wide set of CAM functions since the interruption times are in good agreement with most of the target values in D2.5 [3] for the handover KPIs (TE-KPI2.x) (see also Section 5). It must be noted that these results are independent of the type of inter-PLMN interconnection, internet or direct (XBI_3). In addition, ES-PT shows how the stability of the network allows for a high rate of handovers while maintaining the connectivity in all the cases.

The mobility interruption time in the case of an LBO setup is nowadays strongly dependent on the modem's drivers because there is not yet a standardized firmware to trigger the change of session from the network side. The values obtained in both CBCs are of the order of seconds, making quite difficult the execution of any CAM service in safety conditions.

4.2. XBI_2: SA Roaming interruption

Interruption during roaming between 5G SA networks poses a similar issue to CAM applications as roaming between 5G NSA networks, presented in the previous section. When a UE loses the signal to an SA network, the data flow for the application is interrupted and the UE is forced to establish a new connection to another SA network before the service can be continued. A solution is for the gNB to actively release a UE from the first network, and redirect it to the next en-route network in order to reduce the roaming interruption time. The effectiveness is measured by the roaming handover success rate (TE-KPI2.2) and the roaming interruption time (TE-KPI2.3). This solution was only tested at the NL TS in the Extended Sensors UCC and the Collaborative Perception Messages (CPM) US (Table 9).

Table 9: Summary of UCC/US where XBI_2 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_6: Release and redirect using an SA network	NL	Extended Sensors	CPM	NL-1.8 to 1.11, NL-3.4

4.2.1. CS_6: Release and redirect using a SA network

NL TS

The test route in the NL TS is covered by two 5G SA test networks from KPN and TNO with LBO roaming. Each network has a LBO. For this test, a single MQTT server is used in the MEC to exchange messages between UEs with their respective network as shown in Figure 12. Note that this setup is a simplification of the inter-MEC exchange in section 4.5.6.

In the Extended Sensors US, two test vehicles are connected to their TNO home network and exchange CPM messages to support lane changing. Somewhere halfway the test route, the two vehicles have to roam from their home network to the visited KPN network.

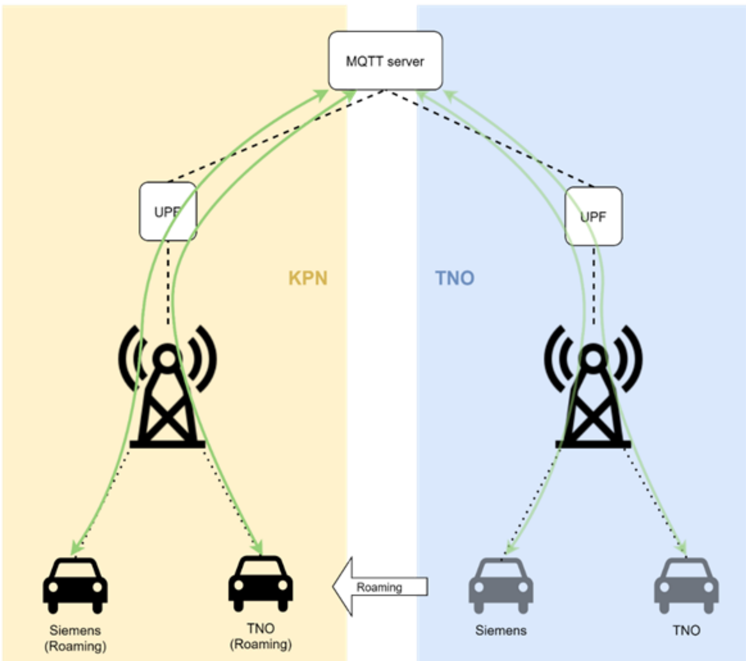


Figure 12: NL TS, SA roaming network setup

LBO roaming involves several steps that contribute to the roaming and service interruption:

1. When the signal strength drops below a threshold value, the UE is released from the cell and network. The release is initiated by either the UE itself or by the gNB.

2. The UE has to search the frequency band for a visiting network. When found,
3. the UE has to attach to the visiting PLMN,
4. restore the IP network connection in the V-PLMN,
5. connect to the MQTT server and subscribe to the CPM data flow, and
6. the application resumes the lane changing service.

Release and redirect solutions address the first two steps and are implemented and evaluated in three scenarios:

Default roaming is a reference situation, in which the UE has to detect signal loss, disconnect and search all frequencies for a new network to connect to. The UE is not released by the gNB of the home network and does not receive any information to direct it to the visiting network (i.e., KPN).

Semi-optimised roaming is an intermediate solution in which the UE is released once the signal drops below a threshold. The UE receives information to redirect it to the nearest network to visit. The UE has the configuration information of the KPN network but it does not receive the frequency band of the KPN network though, so it still needs to search multiple frequencies in step 2.

Optimised roaming releases the UE and provides all necessary information to the UE, including the scan frequency, to further reduce the search to the visiting KPN network in step 2.

Detailed architecture and setup of the communication network, roaming, release and redirect configurations are presented in D3.7 [1], section 9. Dynamic release of the UE by the gNB in step 1 is realised. Agnostic tests showed that the gNB has a higher threshold on the signal loss and releases earlier than the UE does on its own in the default roaming scenario (NL-1.9). From the RSRP it is estimated that the gNB releases the UE a few seconds earlier, which is typically the last period in the home network where the network connection has already deteriorated and the service is already interrupted.

Due to technical challenges, mainly with the UE not attaching to the directed network (see also section 6.3), the redirect solution could not be fully made to work in a dynamic and automated manner. Consequently, the application could also not be tested with dynamic release. Instead, information to redirect to the visiting PLMN was pre-configured on the SIM cards of both test vehicle UEs. This is a tailored solution that does not scale to real world applications; an MNO will most likely not be able to implement the optimized scenario in this way. However, when the Release & Redirect would be fully implemented and comparing that to the pre-configured optimized scenario, the optimized scenario should yield comparable interruption times; the 'Redirect' in Release & Redirect should allow directing a UE into a specific search frequency (e.g., ARFCN). The main difference would be that the gNB would release a UE earlier and reduce the interruption time by a few seconds.

Roaming interruption time is measured as the time period during which network connection to both the home and the visiting network is lost; i.e. steps 1-4. Network connection is measured using repetitive ping tests in which a new ping is sent within 10 msec after receiving the pong to the previous ping or after a lost ping. Roaming interruption time is measured as the time between the last successful ping test in the home network and the first successful ping test in the visiting network. The network connection (TAC) and cell ID are recorded with 1 Hz frequency, together with signal strengths (RSRP) at the access layer to distinguish cell handovers from roaming.

Table 10 summarises the roaming performance in the NL TS for the test cases (NL-1.8 to 1.11) of a single UE. All handovers are successful. Most interesting is the significant reduction in interruption time than can be accomplished from more than 1 minute with default roaming to 14 – 16 seconds when a UE is redirected to the PLMN ID and frequency band of the adjacent network. Nevertheless, an interruption time of 14 seconds is below the requirements of CAM applications such as lane changing, and still significantly larger than inter-cell handovers (less than 1 second).

Table 10: NL TS, TE-KPI2.2 - Roaming Handover Success Rate and TE-KPI2.3 – Roaming Interruption Times in the Extended Sensors US

Roaming	Nr of test runs	Roaming Handover Success Rate	Roaming Interruption Times [seconds]						
			avg	median	stdv	max	min	CI 95	Perc. 95
Default	4	100%	75.2	74.5	3.1	78.5	72.5	7.7	78.1
Semi-Optimised	4	100%	33.7	33.2	1.7	36.3	32.2	2.8	35.8
Optimised	5	100%	14.5	14.1	0.6	15.1	14.1	1.5	15.0

Service interruption is even larger than the roaming interruption measured in Table 10. Even in the optimised roaming setup, service interruption times in the order of 1 minute are measured. The service interruption is significantly higher than roaming interruption mainly because of two reasons. The two UEs in the test vehicles release and start roaming asynchronously, so the effective interruption is larger than the roaming interruption of a single UE. Once a UE is connected to the visiting network, it has to reconnect and subscribe to the MQTT server. Establishing the MQTT connection and receiving the first CPM message may take more than 30 seconds. Detailed results on roaming and service interruption times are provided in Appendix.

In the Remote Driving US, similar tests are performed with the same network setup and semi-optimised roaming in test case NL3-4. In this US only 1 UE has to roam to the visiting network and restart streaming on-board video. The service interruption times for a single UE are between 61 and 82 seconds, see Appendix.

The default settings for reconnecting and subscribing to the MQTT server are used in the NL TS which may increase the service interruption by half a minute or more. This causes the largest extra delay and cannot be attributed to the 5G network; this is a concern for MEC services that needs to be addressed in a next project (section 6).

4.2.2. Conclusions

Release and redirect could not be fully realised with the commercial products (motivated in section 6.3), and instead a pre-configured solution to redirect UEs is implemented and tested. This should yield comparable results for the roaming interruption times, albeit that the gNB would release a UE earlier than the UE would by itself, thereby reducing the effective interruption time by a few seconds (in this setup). Dynamic redirection by the gNB would yield the same improvement as the pre-configured optimised solution tested.

Redirection of a UE avoids searching for a new network (V-PLMN and frequency) and can reduce roaming interruption by about 1 minute. Although this is a significant improvement, the optimised roaming time is still 14 – 16 seconds, which is significantly exceeding the application requirements.

The registration to the visiting network and restoring an IP network connection still takes considerable time; i.e the larger part of the 14-16 seconds of the roaming interruption. This needs to be improved as well to meet the application requirements.

4.3. XBI_3: Inter-PLMN interconnection latency

Currently operators typically interconnect through a GRX/IPX 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 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. The direct interconnection between the applications supporting the local vehicles reduces the number of hops and therefore the E2E latency.

In the following, it is explained the conditions under which the aforementioned KPIs were measured, and compared the results derived in the cases of the internet-based interconnection (CS_7) and direct (leased line) interconnection (CS_8). Table 11 provides a summary of UCC/US where XBI_3 was trialled in ES-PT and GR-TR.

Table 11: Summary of UCC/US where XBI_3 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_7: Internet-based Interconnection	GR-TR	Vehicles Platooning	See What I See	GR-TR-11.1
		Extended Sensors	Assisted Border Crossing	GR-TR-4.1 and GR-TR-7.1
CS_8: Direct interconnection comparison	ES-PT	Advanced Driving	Lane Merge	ES-PT-1.1, ES-PT-1.2 and ES-PT-1.4
			Overtaking	ES-PT-2.1 to ES-PT-2.6
			Cooperative Automated	ES-PT-5.6 and ES-PT-5.7

		Extended Sensors	HD-Maps Vehicle	ES-PT-3.1, ES-PT-3.2 and ES-PT-3.4
	GR-TR	Vehicles Platooning	See What I See	GR-TR-11.1
		Extended Sensors	Assisted Border Crossing	GR-TR-4.1, GR-TR-4.2 and GR-TR-4.4 GR-TR-7.1, GR-TR-7.2 and GR-TR-7.4
			Truck Routing	

4.3.1. Comparison of CS_7 (internet-based interconnection) and CS_8 (direct interconnection)

GR-TR CBC

The results in the paragraphs that follow are related to the Assisted Zero-Touch Border Crossing US. The measurements reported from the application side are logged using a COSMOTE (GR network) SIM card with the UE residing at the visited TR PLMN when measuring and represent the E2E latency (RTT) experienced between the OBU and the respective server (either GR edge, TR edge or cloud server). Different trials were performed with a cloud server and two edge servers, one located on the GR side of the borders and one located at the TR side of the borders.

Table 12 depicts the average E2E latency from an application perspective for the two considered solutions (CS_7 and CS_8). The results are presented separately for the case of the cloud server scenarios and the edge server scenarios.

Table 12: GR-TR CBC, overview of the E2E latency experienced from the application side in Assisted Zero-Touch Border Crossing case

E2E latency for HR (CS_17)	test case	samples	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI 95(ms)	Perc. 95 (ms)
Cloud Server									
Public Internet (CS_7)	GR-TR-4.1 GR-TR-7.1	20632	261	113.8	329.1	1787.1	29	[256,265]	1181
Direct Interconnection (CS_8)	GR-TR-4.2 GR-TR-4.4 GR-TR-7.2 GR-TR-7.4	47289	133	106.8	984.65	1585.65	27.38	[124,142]	249
GR Edge Server									
Public Internet (CS_7)	GR-TR-4.1 GR-TR-7.1	28774	117	74.7	133.77	1415	12.02	[116,119]	260

Direct Interconnection (CS_8)	GR-TR-4.2 GR-TR-4.4 GR-TR-7.2 GR-TR-7.4	34068	82.6	74.37	46.23	1203	12.22	[82,83]	131
TR Edge Server									
Public Internet (CS_7)	GR-TR-4.1 GR-TR-7.1	5175	553	294.77	133.77	1359	26.97	[542,564]	1115
Direct Interconnection (CS_8)	GR-TR-4.2 GR-TR-4.4 GR-TR-7.2 GR-TR-7.4	3094	268	263.5	46.69	1006	80.19	[167,270]	335

The improvement in terms of E2E latency when a direct interconnection is used between the two PLMNs (CS_8), instead of a Public Internet interconnection, is clear for all scenarios. The benefit ranges from 29% to 51% of E2E latency reduction.

The experienced RT time for communication between the OBU and the cloud server is enough to adequately perform most of the envisioned functions of the US. The average experienced inter-PLMN interconnection latency significantly increases when the UE (with a GR SIM card) resides at the visited PLMN and it used the local (visited) edge server (TR), reaching an average value of 553 ms. This is a direct consequence of the HR scheme (CS_17) which forces the traffic to reach the local edge server through the (remote) Home PLMN. This points out the need for either a LBO solution to directly take the traffic to the local edge server, or avoid mis-configurations at the application layer i.e., resolving to a local edge server in the presence of HR. When the edge server resides at the Home PLMN (under the HR configuration) we also anticipate the benefits of edge computing, in this particular setup, where the E2E latency is significantly improved compared to the setup of a cloud server (from 261 ms to 117 ms). Moreover, a more stable performance with less variations is observed.

When CS_8 is used, the RT time is significantly improved. The experienced RT time for communication between the OBU and the edge server via the H-PLMN is enough to adequately perform all the envisioned functions of the US. The average performance is quite satisfactory in terms of the target values in D2.5 [3].

The results in Table 13 and Table 14 are related to the Platooning with See-What-I-See video streaming functionality. The measurements reported from the application side are logged using two COSMOTE (GR network) SIM cards and represent the E2E latency experienced between the application devices behind the IMEC OBUs (as they were positioned in the respective trucks) and the respective server. Different trials were performed with the two edge servers, one located on the GR side of the borders and another one located at the TR side. The total aggregated E2E latency between the client device which initialized the video streaming and the screen of the recipient client device is given in average in the following tables.

The outcome confirms that the average E2E latency referring to the See-What-I-See application perspective gives significantly betters latency results in the case of direct interconnection. The maximum values are due to the somehow better link qualities while considering also some outlier values during handovers. The application worked and was tested on one edge server per test case and run. The following results from the See-What-I-See application refer to the average values per case derived from DEKRA tool. The video streaming-related results can be comparable with the respective ones of FI site and its video streaming case. Based on this, the 3ms level is correct due to the data rates pointed out during the experiments and the conventional video streaming quality (not High Definition).

Table 13: GR-TR CBC, total E2E latency in the case of public internet connection in See-What-I-See case

GR EDGE APPLICATION SERVER			
Samples	**Mean**	**Median**	**Std. Deviation**
480	103.6 ms	101.4 ms	19.62 ms
Max	**Min**	**CI 95%**	**Percentile 95%**
117.13 ms	104.33 ms	2.43 ms – 3.68 ms	3.478 ms
TR EDGE APPLICATION SERVER			
Samples	**Mean**	**Median**	**Std. Deviation**
480	117.4 ms	105.43 ms	21.75 ms
Max	**Min**	**CI 95%**	**Percentile 95%**
122.55 ms	108.21 ms	2.73 ms – 3.94 ms	3.501 ms

Table 14: GR-TR CBC, total E2E latency in the case of direct interconnection in See-What-I-See case

GR EDGE APPLICATION SERVER			
SAMPLES	**Mean**	**Median**	**Std. Deviation**
480	43.2 ms	43.31 ms	12.31 ms
Max	**Min**	**CI 95%**	**Percentile 95%**
159.19 ms	17.424 ms	1.62 ms - 1.72 ms	1.522 ms
TR EDGE APPLICATION SERVER			
SAMPLES	**Mean**	**Median**	**Std. Deviation**
480	48.83 ms	47.62 ms	16.25 ms
Max	**Min**	**CI 95%**	**Percentile 95%**
163.28 ms	21.473 ms	1.74 ms – 1.92 ms	1.911 ms

FI TS contribution to GR-TR CBC

FI TS contributed in the See-What-I-See application of the GR-TR CBC with the LEVIS server and client transfer during its deployment and tests. More particularly, the LEVIS video streaming which was used on the Remote Driving US of FI TS was adapted, integrated with the See-What-I-See application management module and installed in both the server and clients equipment used for the application development. The aforementioned contribution focuses on the cross-border scenarios on GR-TR CBC TS in which all OBUs have to make a hand over between the GR COSMOTE and TR TURKCELL networks. Based on the LEVIS application's performance, the See-What-I-See demonstrated comparably satisfactory results at both data throughput, latency and reliability. Referring to the latency and the specific XBI, the UL latency of LEVIS video streaming was 41 ms in average, a comparable value with the average latency of the See-What-I-See application latency (45.6ms) as it is indicated in Table 14. In terms of reliability, the See-What-I-See application achieves the same level as the LEVIS video streaming in the Remote Driving case of FI TS.

ES-PT CBC

ES-PT has designed a direct interconnection between NOS and TELEFÓNICA networks by interconnecting the central cores and the distributed cores (located in the area of the trials and separated by 70 km) through two transport networks. The traffic is routed by a dedicated fibre between both networks to increase the efficiency, otherwise, the peering mechanisms would add tens of ms (as demonstrated in D3.7 section 4.1) that would compromise most of the ES-PT CAM services. This architecture is especially suitable for the CAM functions in HR configuration (CS_17) requiring very low latency, as is the case of Advanced Driving US.

Advanced Driving test cases are based on the interchange of ETSI messages between the OBUs and the two instances of an MQTT broker in the ES and the PT MECs. In the cross-border tests, the messages travel through the inter MECs topics of the Geoservers to provide the information to the vehicles involved in the manoeuvre with both TELEFÓNICA and NOS SIMs.

Table 15 shows the latency values in a test on the national side (ES-PT-2.1) and another on the cross-border (ES-PT-2.2). Cross-border latencies are higher due to the interconnection and the handover effects, which causes also great deviations between the average and the median values. The difference values between both tests are higher in UL than in DL because of the asymmetric network configuration.

Table 15: ES-PT CBC, UL and DL latencies at the network and the application layers for the CAM messages exchanged between two vehicles through the ES and PT MECs

<table>
<tr><th>Tests ID</th><th>Layer</th><th>Flow</th><th>avg (ms)</th><th>median (ms)</th><th>std (ms)</th><th>max (ms)</th><th>min (ms)</th><th>CI 95 (ms)</th><th>Perc. 95 (ms)</th></tr>
<tr><td rowspan="4">ES side (ES-PT-2.1)</td><td rowspan="2">Network</td><td>UL</td><td>17.8</td><td>16.7</td><td>6.1</td><td>255</td><td>5.2</td><td>17.7-17.8</td><td>27.9</td></tr>
<tr><td>DL</td><td>7.1</td><td>6.3</td><td>9.2</td><td>1577</td><td>4.8</td><td>7.0-7.2</td><td>11.1</td></tr>
<tr><td rowspan="2">Application</td><td>UL</td><td>21.8</td><td>20</td><td>9.9</td><td>625</td><td>6.0</td><td>21.7-22.0</td><td>33</td></tr>
<tr><td>DL</td><td>39.1</td><td>42.0</td><td>48.8</td><td>1587</td><td>7.0</td><td>38.5-39.7</td><td>55</td></tr>
<tr><td></td><td>Network</td><td>UL</td><td>53.4</td><td>23.2</td><td>228.5</td><td>5511</td><td>6.5</td><td>47.9-58.9</td><td>135</td></tr>
</table>

Driving from PT to ES (ES-PT-2.2)		DL	9.5	26.6	860	860	5.2	14.9-15.9	56.6
	Application	UL	252	32	709	6316	9.0	238-265	1390
		DL	36.2	19.0	49.2	857	8.0	35.3-37.2	102

Table 16 compares the E2E latency results of two test cases when driving from PT to ES to see the effect of the distance to the MQTT on the latency. In ES-PT-2.10, both vehicles are sending and receiving CAM messages with TELEFÓNICA SIMs and in ES-PT-2.11 the vehicle uploading the CAM messages have the TELEFÓNICA SIM but the vehicle receiving the NOS one. The statistics of these test cases for the E2E latency are obtained for the full route including the sections before the handover, during the handover and after the handover. ES MEC is closer to the trial scenario so the E2E latency is shorter accordingly.

Table 16: ES-PT CBC, E2E latency values at the network and the application layers for the CAM messages exchanged between two vehicles from PT to ES in overtaking US

Test	layer	avg (ms)	median (ms)	std (ms)	max (ms)	min (ms)	CI 95 (ms)	Perc. 95 (ms)
ES SIM in both vehicles (ES-PT-2.10)	Network	60.7	60.5	35.0	529	17.7	58.7-62.8	119
	Application	104.6	70.0	171.4	2053	22.0	100.6-108.6	309
ES SIM in UL and PT SIM in DL (ES-PT-2.11)	Network	63.3	45.9	39.7	499	21.3	61.5-65.1	133.5
	Application	88.5	58	99.2	2234	24.0	86.1-90.8	207

The difference in the results at the network layer and at the application layer reveals interesting conclusions from the implementation point of view. Figure 13 presents an illustrative example of the impact of the application layer in the E2E communications when the CAM messages between the two vehicles are exchanged through the ES and the PT MECs. It shows the segmentation of the latency values when running an overtaking test from PT to ES with ES SIMs in both vehicles (test run from ES-PT-2.2). As the network configuration is not symmetric, the impact of the handover is stronger in UL (blue and orange bars) than in DL (red and black bars), showing higher latencies that, in addition, last a few seconds after the change of the network (blue and orange bars when vehicle 1 is sending the CAM messages performing the handover, and red and black bars when vehicle 2 is receiving such messages crossing the border). During this time, the contribution of the transport protocol is also significant because the TCP queues the messages due to the delay in the ACKs messages, ensuring, on the other hand, values of reliability over 99%.

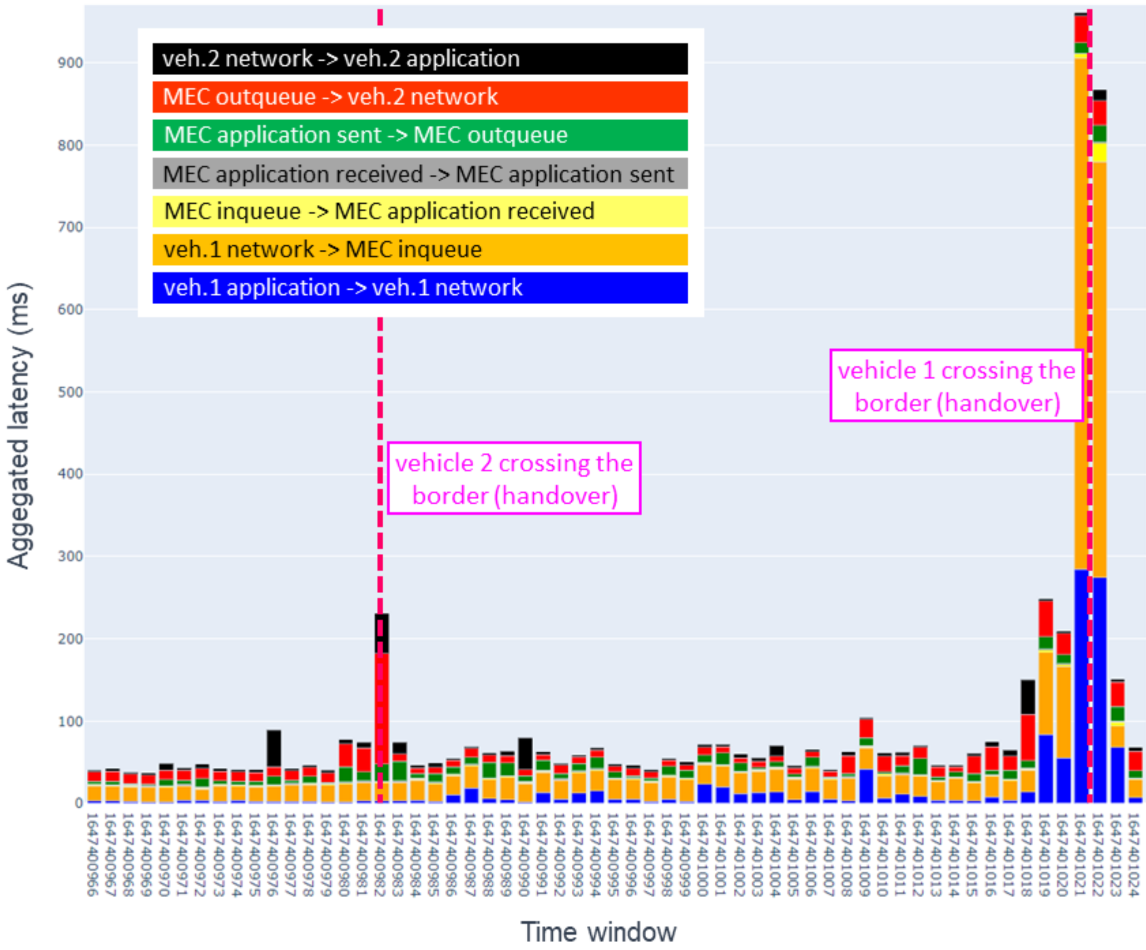


Figure 13: ES-PT CBC, E2E latency in an overtaking test case (V1 is the vehicle sending the CAM messages to V2)

As a side result, the tests have also revealed how the use of many flows on the driving function affects the overall connectivity. Table 17 compares the UL latency at the network layer, on the ES side and the cross-border situation, for a flow of CAM messages when there is no other flow in the test (ES-PT-2.1 on ES side and ES-PT.2.2 in the cross-border, overtaking) and when the vehicle is uploading in parallel a large file (ES-PT-3.1 on ES side and ES-PT-3.2 in the cross-border, HD-Maps). Values are substantially higher for the latter.

Table 17: ES-PT CBC, impact of the load of the network on the UL latency at the network layer in CAM messages

Test	load	avg (ms)	median (ms)	std (ms)	min (ms)	max (ms)	CI 95 (ms)	Perc.95 (ms)
ES side in overtaking (ES-PT-2.1)	No	18.3	16.6	5.9	8.3	42.6	18.1-18.5	27.8
ES side in HD-Maps (ES-PT-3.1)	Yes	78.7	59.5	50.3	7.3	364.7	76.0-81.3	185.7
PT to ES with ES SIM in overtaking (ES-PT-2.2)	No	57.8	21.3	261.5	6.7	5128	52.0-63.7	126.0
PT to ES with ES SIMs in HD-Maps (ES-PT-3.2)	Yes	58.1	55.1	31.0	6.1	200.2	57-59.2	113.5

Regarding the Remote Driving US, the impact on the network is quite significant compared to the application processing tasks as asynchronous UDP commands for control protocol and RTP video packets are not queued. Instead, they are just discarded when they are not received.

One important thing to consider in this use case is that only one instance of the server in the MEC(ES) is used in these executions. This is different from the HD-Maps and overtaking use cases, in which 2 VM instances are used in the handover scenario. The traffic is forwarded directly to the ES VM instance regardless of the location of the vehicle.

The handover peak reach values of 375 ms as it can be seen in Figure 14. This is close to the limit of supported value for the use case. In this situation the network is being stressed with additional load from the video streams used for Remote Driving.

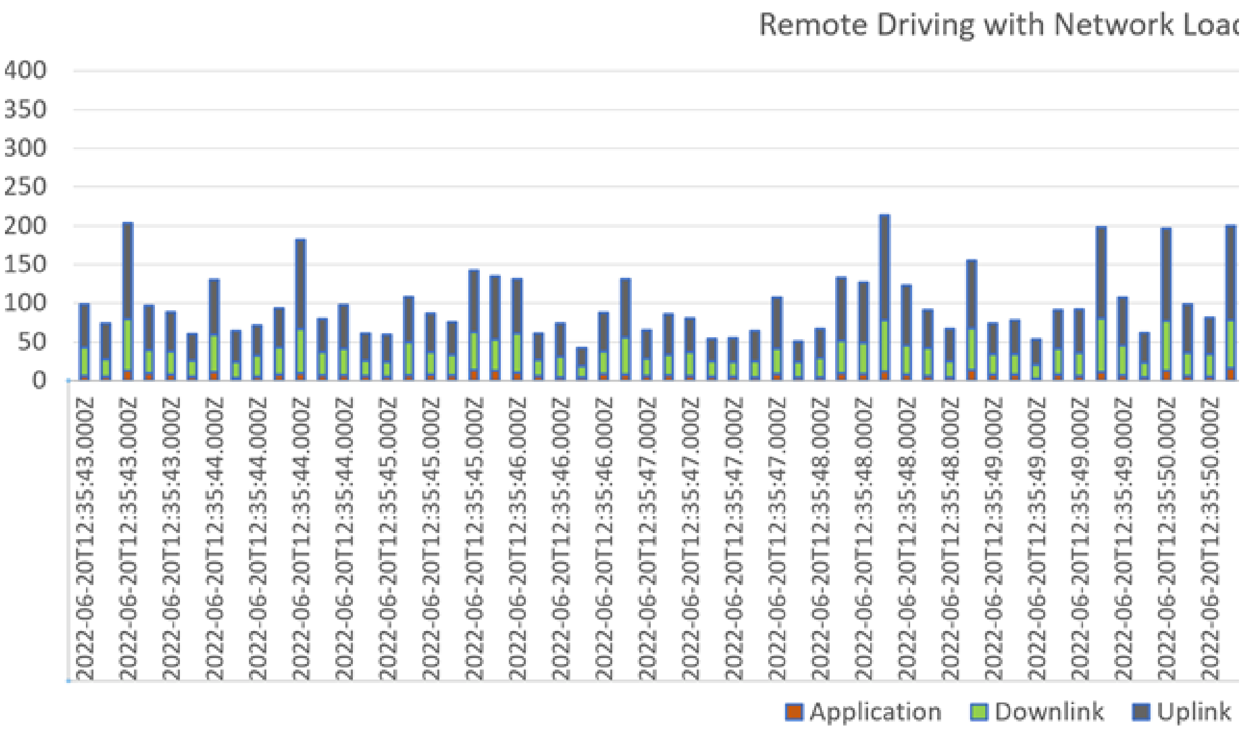


Figure 14: ES-PT CBC, RTT Latency(ms) in Remote Driving US with traffic load

The average RTT latency is below 100 ms (Table 18) which allows the protocol to work under default configuration. There is a slight increase in latency around the handover event. However, this does not impact the standard deviation substantially, meaning that overall, a high level of stability is ensured. The latency has been measured using accurate tracing in the application control plus the detailed tracing in the MEC which are NTP synchronized with the rest of the network components. The E2E latency is the cumulated uplink + downlink + application time, which represents a RTT latency. The measurements are taken around the interval of the handover procedure at 12:35:48. Before that time normal traffic without handover is represented.

Table 18: ES-PT CBC, impact of network latency in RD application

Tests	Layer	avg (ms)	median (ms)	std (ms)	max (ms)	min (ms)	CI 95 (ms)	Perc.95 (ms)
PT to ES with ES SIMs (RD Video)	Network	93.77	80.45	49.44	350.08	34.36	79.94-80.96	109.44
	Application	101.44	86.95	53.43	375.56	36.22	77.55-96.35	202.72

When the Remote Driving protocol latency is compared with the same situation but without traffic load (Table 19) the network latency is about 60 ms better, which shows the impact of the network traffic in the use case. In this case only the network part of the latency is considered.

Table 19: ES-PT CBC, impact of data traffic in RTT for Remote Driving protocol

Test	load	avg (ms)	median (ms)	std (ms)	min (ms)	CI 95 (ms)	Perc.95 (ms)
ES side with RD	No	33.10	30.70	14.26	13.65	30.62-30.78	58.17
PT to ES with ES SIMs (RD Video)	Yes	93.77	80.45	49.44	34.36	71.75-89.15	188.50

4.3.2. Conclusions

The comparison of the E2E RT latency values between the internet and the direct interconnections of GR and TR networks showcases a significant reduction when the connection is through a leased line and with edge servers (benefits in the 29%-50% range). Moreover, results show the importance of a careful service configuration when HR (CS_17) is employed, since in that case the use of a local application/edge server at the visited PLMN results in suboptimal routing (which even in the presence of a direct interconnection, yield high E2E latencies). Furthermore, the results quantify the benefits of edge computing in the considered deployments, showing an average latency reduction in the range of 50 to 144 ms, with a notably more stable behaviour. The results in ES-PT also evince the increase in E2E latency when trialling on the national side compared to when trialling in the cross-border due to the highest latencies in the handover process and also the TCP mechanisms at the transport layer. These values E2E values are longer when the communication channel has to handle additional data flows.

The latency values for the direct interconnection in ES-PT and GR-TR (GR edge) are directly comparable, pointing out again to the reproducibility of results in the two CBC.

4.4. XBI_4: Low coverage Areas

The analysis of the low coverage areas is focused on the levels of throughput and E2E latency along the cross-border area in order to identify gaps in the CAM application continuity. XBI_4 was tested by the FR TS through the satellite connectivity (Table 20).

Table 20: Summary of UCC/US where XBI_4 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID

CS_9: Satellite connectivity	FR	Agnostic	NA	TCA-FR-12 and TCA-FR- 13
		Advanced Driving	Assisted Infrastructure	FR-1.6

4.4.1. CS_9: Satellite connectivity

FR TS

Low Earth Orbit (LEO) satellite communication is considered as an alternative technology to provide connectivity to the vehicle when it is out of coverage of any 5G network. FR TS evaluated a system which can deliver such connectivity in different conditions:

- UCC/US agnostic tests have been done with a multi-modem solution to validate the ability to keep connection alive when no 5G network is available.
- UCC/US specific tests have been done with satellite communication only to assess the performance of this technology in supporting the Advanced Driving from Assisted Infrastructure use case. In such use case, a remote V2X server is responsible for monitoring status of a connected and automated vehicle (CAV). For this, on important requirement is to ensure upload of CAM packets with few kilo bytes at a frequency between 1 and 10Hz.

The solution has been implemented using a satellite communication terminal connected to the iridium constellation (Iridium Certus service) available worldwide thanks to 66 cross-linked satellites and expected to provide data rate of few hundreds of kbps.

First of all, delay tests were carried out with a ping (FR-1.6) that showed results with delays up to a few seconds (up to 14) as illustrated in Figure 15 and Table 21. For that purpose, permanent pings were sent from the vehicle to the MEC and during the first 100 seconds the response time around 400 ms was acceptable, then it grows up to 14 seconds, thus generating the closing of the communication established. Additionally, TCP traffic tests have been carried out with Iperf showing average transfer data rate of 116kbps in UL (from vehicle to MEC) and 95.6 kbps in DL (from MEC to vehicle) which is lower to values expected with this technology.

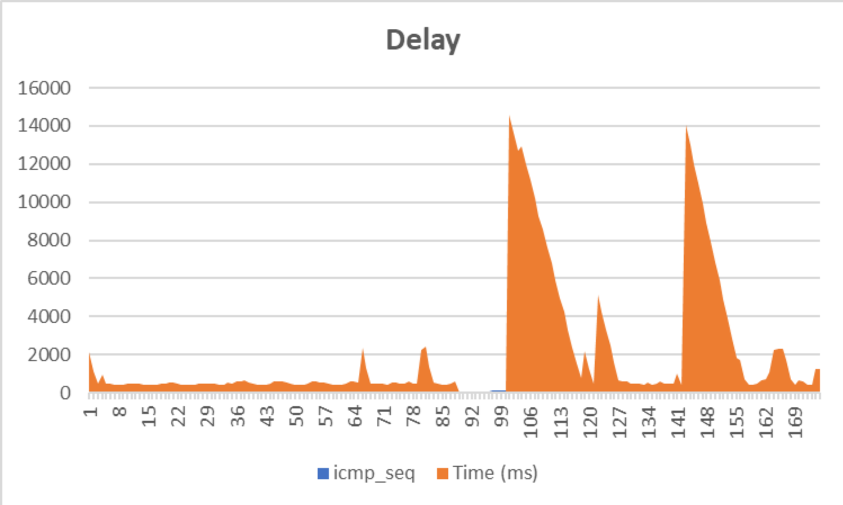


Figure 15: FR TS, delay performance measured with satellite technology

Table 21: FR TS, delay performance measured with satellite technology

Test	avg (ms)	median (ms)	min (ms)	max (ms)
FR-1.6	1978	725	500	15200

Second, this solution is considered in the low coverage areas where 5G communication is not present. Then, it has been tested in FR TS in combination with 5G private network with limited coverage (TCA-FR-12 and TCA-FR-13). During the test, a vehicle drives at low speed (about 50 km/h) from an area covered by 5G to an area out of coverage. To handle multi-technology communication, satellite communication terminal and 5G modem are tested with an intelligent router for switching from one technology to another one. Two configurations have been set up to be able to compare the results.

- Passive mode, where priorities are assigned to both technologies and data packets are transmitted according to predefined rules such as respective priorities given to the different SIM including the satellite one

- Link aggregation mode, where the intelligent router aggregates data from the two communication links (5G and Satellite) and data packets can be transmitted using both interfaces. In that case, the intelligent router decides which channel has to be used for each packet.

With the first configuration (passive mode in TCA-FR-12), the connection time with the satellite is too long (few seconds) and consequently the connection between the vehicle and the V2X services stops. We can see that when looking at the transfer data rate that was several Mbps while under 5G connection and falls to zero when trying to attach to the satellite communication.

During the UCC/UC agnostic tests, only second configuration (link aggregation mode in TCA-FR-13) was successful. Indeed, when the vehicles leave coverage of 5G network, it can use only satellite communication link and the time required to switch from 5G to satellite in passive mode has been too long to maintain connection with the test server (Iperf). Thus, setup with link aggregation was more robust and results with the configuration can be presented here.

Results of the UCC/UC agnostic tests for the second configuration (link aggregation) are illustrated in Figure 16 where colour show the measured throughput. When UE is located within 5G coverage, high throughput up to 80 Mbps can be obtained (depicted in orange and red). However, when it goes out of coverage, low throughput around 100 kbps (illustrated in green) is given by satellite communications.

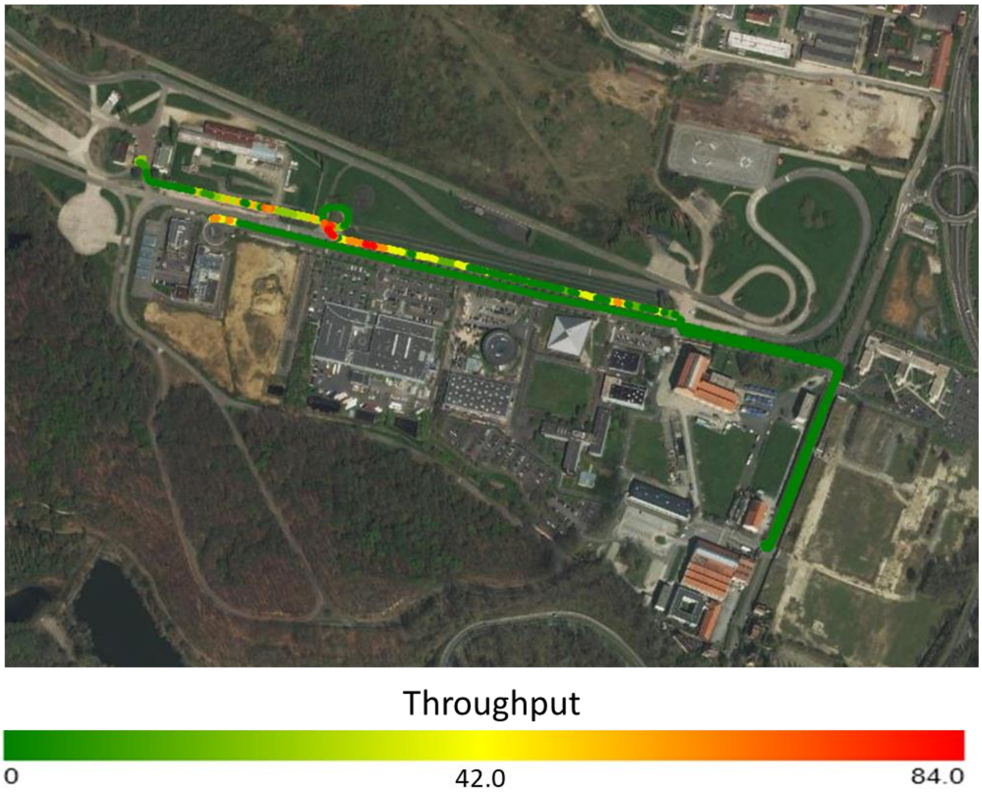


Figure 16: FR TS, route used to test 5G terrestrial to satellite communication technology

4.4.2. Conclusions

The current state of development of satellite solutions is capable of providing a limited level of service which is functional for use cases that require low data rate, for instance, to send CAM messages at a low frequency. The link aggregation mode of the multi-modem multi-SIM OBU provides acceptable interruption times when moving from areas with 5G network to areas out of coverage.

4.5. XBI_5: Session & Service Continuity

When directing the UE to a new 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 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 underlying network changes becomes increasingly important, so as to reduce the impact of mobility and ensure service continuity.

To tackle this issue, project team defined different solution which are listed in Table 22 with relate US and 5G network configuration. Relevant KPIs for this XBI are TE-KPI1.3 (E2E latency) and TE-KPI1.6 (reliability).

Table 22: Summary of UCC/US where XBI_5 was trialled

<table>
<tr><th>CS</th><th>CBC / TS</th><th>Use Case Category</th><th>User Story</th><th>Test Cases ID</th></tr>
<tr><td rowspan="9">CS_4: Multi-modem / multi-SIM connectivity - Passive Mode</td><td>FR</td><td>Agnostic</td><td>NA</td><td>TCA-FR-05 to TCA-FR-11</td></tr>
<tr><td rowspan="3">DE</td><td>Agnostic</td><td>NA</td><td></td></tr>
<tr><td>Extended Sensors</td><td>EDM</td><td>DE-2.1, DE-2.2</td></tr>
<tr><td>Platooning</td><td>AsseRSU</td><td>DE1.2, DE1.3</td></tr>
<tr><td rowspan="3">FI</td><td>Extended Sensors</td><td>Edge Processing</td><td>FI-1.1, FI-1.2</td></tr>
<tr><td>Remote Driving</td><td>Redundant NE</td><td>FI-5.1, FI-5.2</td></tr>
<tr><td>Agnostic</td><td>NA</td><td>TCA-FI-11</td></tr>
<tr><td>CN</td><td>Vehicles Platooning</td><td>Assisted Cloud</td><td>CN-2.1 to CN-2.3</td></tr>
<tr><td rowspan="4">CS_5: Multi-modem / multi-SIM connectivity - Link Aggregation</td><td>FR</td><td>Agnostic</td><td>NA</td><td>TCA-FR-04, TCA-FR-07, TCA-FR-09 and TCA-FR-10</td></tr>
<tr><td rowspan="2">FI</td><td>Remote Driving</td><td>Redundant NE</td><td>FI-3.1, FI-3.2</td></tr>
<tr><td>Agnostic</td><td>NA</td><td>TCA-FI-12</td></tr>
<tr><td>CN</td><td>Remote Driving</td><td>Data Ownership</td><td>CN-3.1,CN-3.2,CN-3.3</td></tr>
<tr><td>CS_10: MEC service discovery and</td><td>ES-PT</td><td>Extended Sensors</td><td>HD-Maps Vehicle</td><td>ES-PT-3.5</td></tr>
</table>

migration using enhanced DNS support	FI	Extended Sensors	Edge Processing	FI-1.1, FI-1.2
CS_13: Double MQTT client	ES-PT	Advanced Driving	Overtaking	ES-PT-2.12 to ES-PT-2.15
CS-14: Inter-MEC exchange of data	ES-PT	Advanced Driving	Overtaking	ES-PT-2.10 to ES-PT 2.15
			Cooperative Automated	ES-PT-5.6 and ES-PT-5.7
	DE	Agnostic	NA	
		Platooning	AsseRSU	DE-1.2, DE-1.3
	NL	Extended Sensors	CPM	NL-1.7
	FR	Advanced Driving	Assisted Infrastructure	FR-1.5
	CN	Advanced Driving	Cloud Assisted	CN-1.1 to CN-1.3
		Remote Driving	Data Ownership	CN-3.1 to CN-3.3

4.5.1. Comparison of CS_4 (Multi-modem / multi-SIM connectivity – Passive Mode) and CS_5 (Multi-modem / multi-SIM connectivity - Link Aggregation)

This section summarizes the results provided by FR, FI and CN comparing the two modes of the multi-modem multi-SIM connectivity (CS_4 vs CS_5) and also the studies of DE in passive mode (CS_4).

FR TS

The FR TS has tested multi-SIM connectivity using an intelligent router able to maintain multiple communication links, hence, providing session and service continuity between different network operators in the context of Infrastructure Assisted Advanced Driving use case.

The solution has been tested in FR TS with 2 5G public networks (ORANGE and BOUYGUES) as shown in Figure 17. During the tests, connected vehicle initially sends traffic over PLMN 1 and, after 30 seconds, the router should switch the traffic to the PLMN 2. The router has been tested in two test cases under different setups. Passive mode (CS_4) and link aggregation (CS_5) were respectively tested in TCA-FR-09 and TCA-FR-08 under good network condition (average SINR is about 21Db).

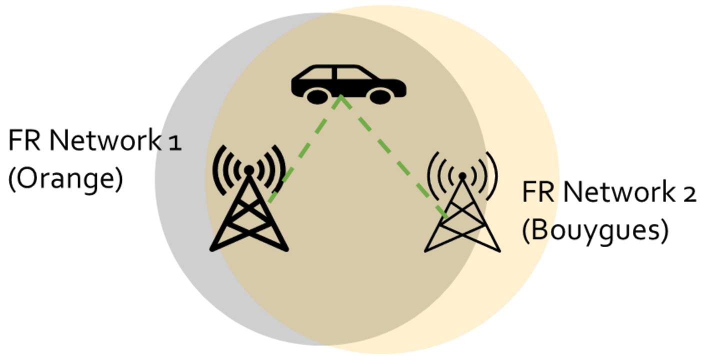


Figure 17: FR TS, 5G Network

Figure 18, Figure 19 and Table 23 illustrate the E2E latency between the UE and a test server installed in the FR TS during the tests of both solution and show average 20 ms with CS_5 and 25 ms with CS_4.

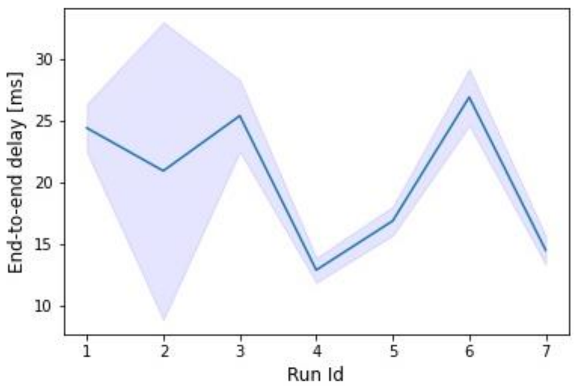


Figure 18: FR TS, E2E latency with CS_5

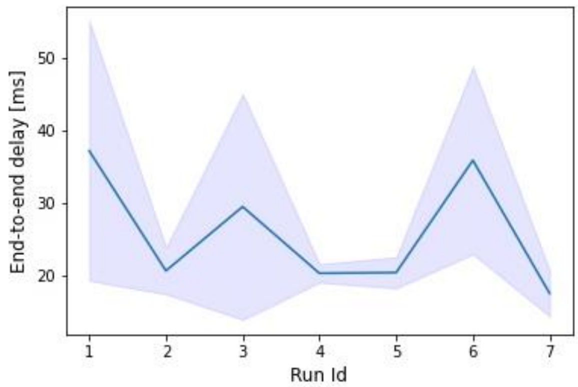


Figure 19: FR TS, E2E latency with CS_4

Table 23: FR TS, E2E latency with passive (TCA-FR-09) and active mode (TCA-FR-08)

Test	avg (ms)	median (ms)	std (ms)	min (ms)	max (ms)	CI 95 (ms)	Perc.95 (ms)
TCA-FR-08	20.0	18.5	48	6.1	58.3	1.79	29.68
TCA-FR-09	26.0	20.0	41.1	10.9	48.0	3.91	32.39

Besides, no packet loss has been experienced with CS_5 ad 0.4% of packet loss was observed with CS_4.

From the test done in FR TS, the main outcomes are:

- Multi-sim connectivity with link aggregation provides the highest performance for service continuity
- Given good network conditions, multi-sim connectivity can ensure service availability

FR TS contribution to ES-PT CBC

A connected vehicle from FR TS was moved to ES-PT in order to test its interoperability with ES-PT connected vehicles, 5G network and digital infrastructure.

Multi-SIM connectivity tests were performed in ES-PT CBC for both Passive mode/CS_4 (TCA-FR-06) and Link aggregation/CS_5 (TCA-FR-07) flavors, where the vehicle drives across the border and switch data transfer from one network to another. During these tests, the vehicle transmits data packets to a server installed in FR.

Figure 20 reports the service interruption time obtained in multi-SIM aggregation mode (TCA-FR-07), in comparison with single SIM (TCA-FR-03) and multi-SIM in passive mode solution (TCA-FR-06). One can see that this mode offers the highest performances with an average interruption of 3.7 s, with a maximum interruption of 12 s during test runs performed at the ES-PT CBC.

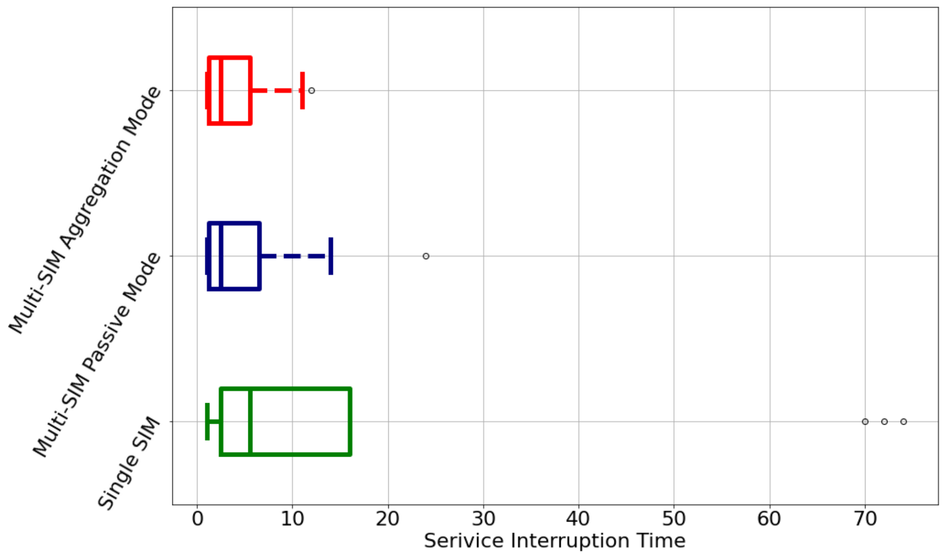


Figure 20: FR TS, service interruption time in seconds obtained with different test cases

In addition, E2E latency between UE and the FR TS server has been measured at ES-PT CBC as illustrated in Figure 21 and Table 24 for CS_5. Its average value lies between 370 ms and 750 ms along the different runs which is higher than the value measured during similar tests carried in FR TS (TCA-FR-09). This can be explained as the main server for the monitoring of traffic with the multi-SIM solution has been installed in FR, resulting in lower latency for tests in the FR TS than in ES-PT CBC. As a conclusion, with such solution, positioning and using a server close to the UE for monitoring the communication link is important to ensure low latency.

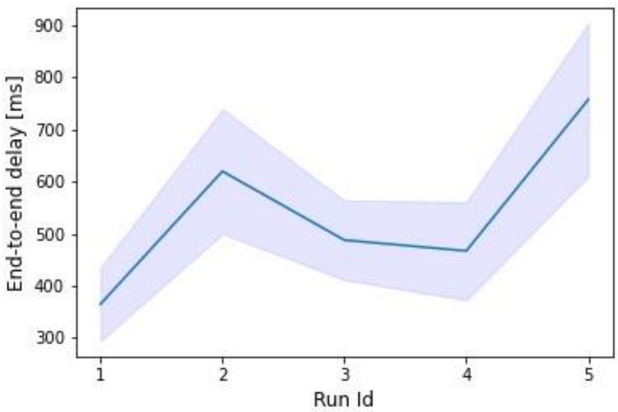


Figure 21: FR TS, E2E latency measure in link aggregation at ES-PT CBC

Table 24: FR TS, E2E latency with passive (TCA-FR-06) and active mode (TCA-FR-07)

Test	avg (ms)	median (ms)	std (ms)	min (ms)	max (ms)	CI 95 (ms)	Perc.95 (ms)
TCA-FR-06	794.23	239.27	1605	39.7	11159	65.46	4410.69
TCA-FR-07	553.43	180.938	1277	40.7	10754	50.2	2854

The FR multi-SIM OBU with link aggregation further participated in the lane merge manoeuvre by exchanging V2X message with ES-PT vehicles through the ES and PT MQTT brokers hosted in ES and PT MECs respectively.

Figure 22 shows the delay on the E2E communication link for messages sent by the ES-PT connected vehicles to the FR connected vehicle. It is worth mentioning that some outliers with values up to few seconds have been observed especially with CAM.

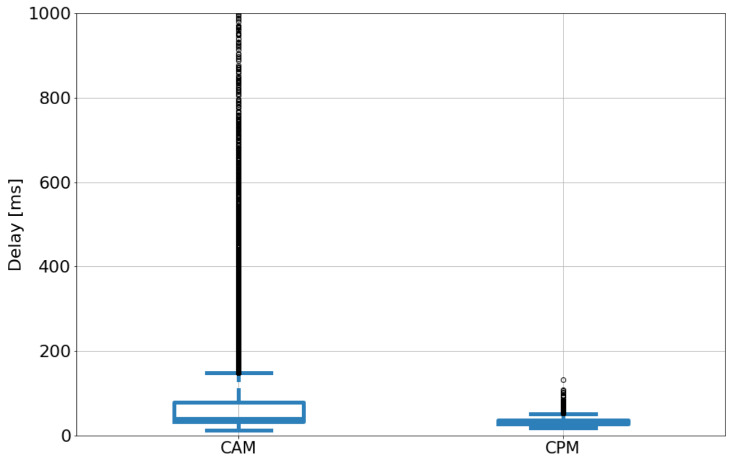


Figure 22: FR TS to ES-PT CBC, E2E delay for CAM/CPM in V2V Communication

These results are comparable to the ones obtained in ES-PT-1.4 from the ES-PT side (Figure 23) between the vehicle performing the manoeuvre (with PT SIM) and one of the vehicles on the road (with ES SIM). The median value is 24 ms showing some outliers due to the handover process.

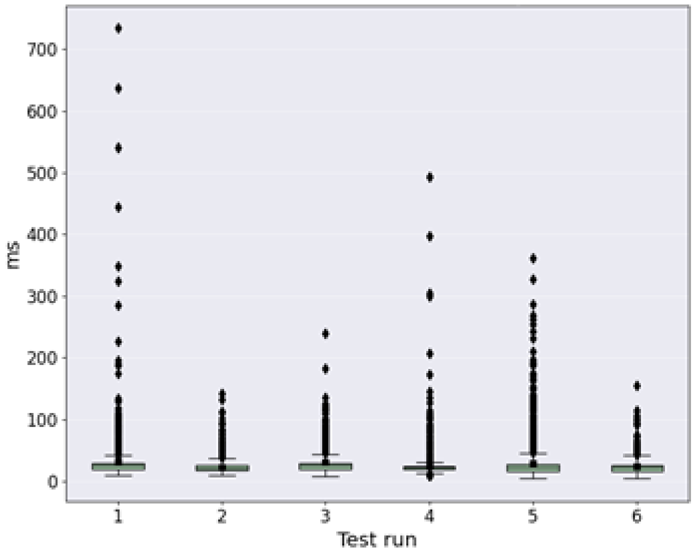


Figure 23: FR TS to ES-PT CBC, E2E delay for CAM in E2E communication with single SIM

This contribution proves the good performance of a multi-SIM OBU in a cross-border environment allowing the correct execution of the tests in a V2X use case.

FI TS

In the FI TS, trials and evaluations were performed to study service continuity when the vehicle is connected in a multi-PLMN environment (two 5G NSA-mode networks) using an OBU with multi-SIM capabilities, operating in link selection (CS_4) mode. These trials included both specific UCC/US trials (for the RedundantNE Remote Driving US) and agnostic trials. In both specific and agnostic trials, single-SIM test cases (with multi-SIM features turned OFF) were implemented to provide a benchmark versus the multi-SIM modes. This subsection focuses on reporting on evaluations for the multi-SIM with link selection mode.

For the Remote Driving US, multiple traffic flows were created in both the uplink (UL) and the downlink (DL) direction. These flows included: two LIDAR streams from vehicle to Remote Operations Centre (ROC) in UL, status messages from vehicle to ROC in UL, HD video streams from vehicle to ROC in UL, and Command messages from ROC to vehicle in DL direction. For the exemplary[6] evaluation results for the Lidar traffic flow in the UL direction are selected. The Lidar traffic flow is UDP with constant bit rate (CBR) of around 7.3 Mbps. The trials were conducted in a FI TS test route covered by two 5G PLMNs (assigned IDs FI-MNO-05 and FI-MNO-06). The result depicted in Figure 24 shows Lidar traffic flow packet loss (for single Lidar

[6] These are representative results showed only for this selected subset of setups, while the remainder, showing similar performance, can be found in FI TS evaluation reports linked in the Appendix

stream) for all test cases (note, the box plot for each test cases considers all the runs for that test case). Improvements with both multi-SIM link selection and link aggregation modes were observed over the corresponding single-SIM test cases (whereby the OBU only attaches to one PLMN throughout the trajectory).

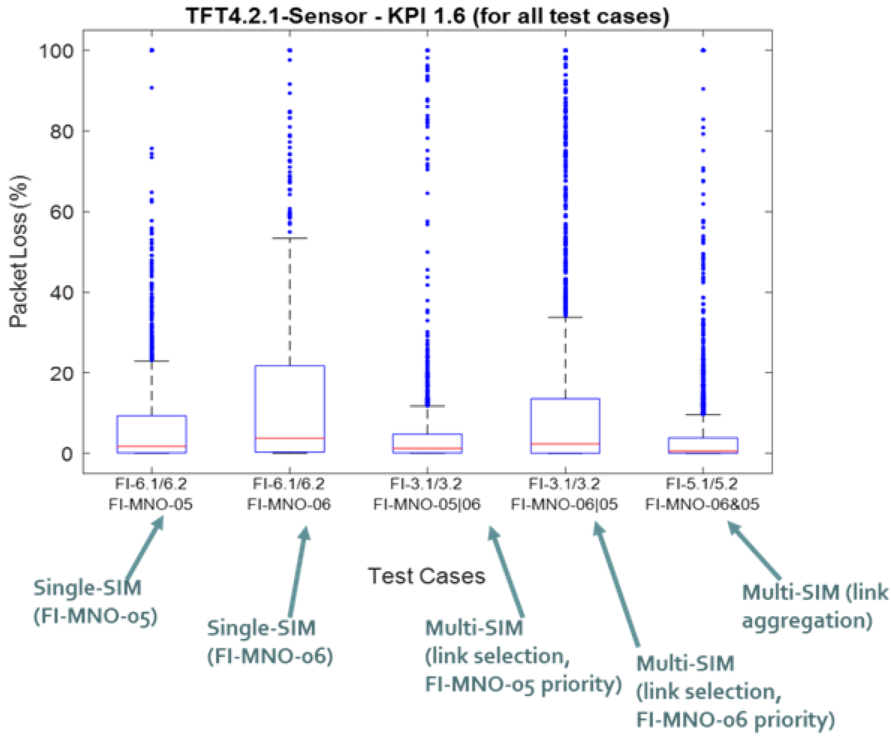


Figure 24: FI TS, lidar traffic flow packet for all test cases

The improvements with multi-SIM are further illustrated in Figure 25 which shows throughput results for Lidar streams in selected test runs for single-SIM and multi-SIM case with link aggregation.

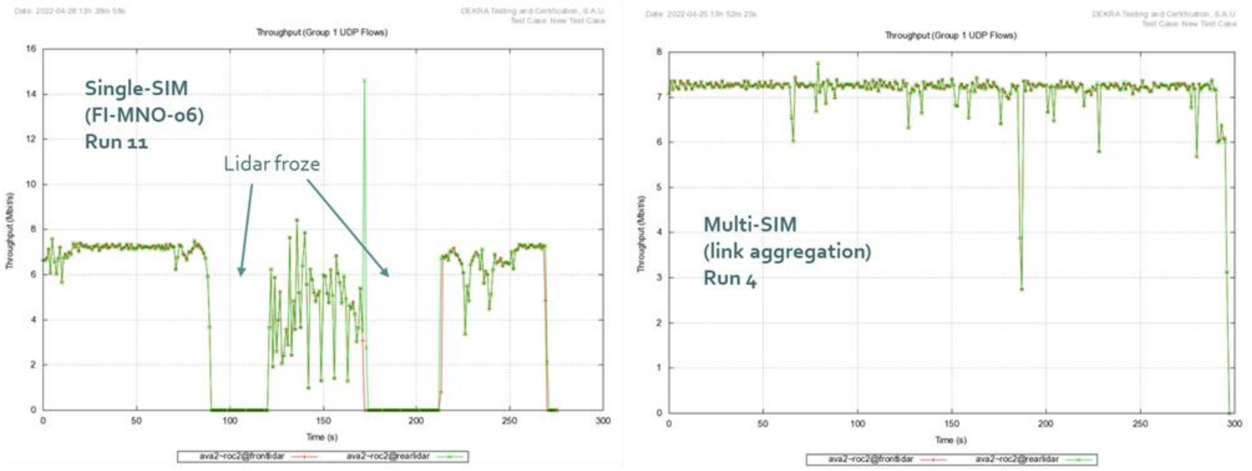


Figure 25: FI TS, example of lidar throughput result from single-SIM test run (left) and multi-SIM link aggregation mode test run (right)

Another interesting result is based on the status messages traffic flow, which has a low-rate (100 kbps) but with more stringent latency requirements (target latency < 160 ms RTT). In Table 25 below, it is actually observed that with multi-SIM link selection mode, frequent link (re-)selection may add latency (compared to single SIM case). Based on the configured quality criteria for network in the multi-SIM OBU, it was observed with link selection mode, network changed on average about every 30 seconds (= every 300 m, assuming average speed of 40 km/h).

Table 25: FI TS, comparison of selected latency statistics for status message traffic messages for all test cases

KPI 1.6: End to end latency (Target ≈ 160 ms RTT)					
Tess Cases →	FI-6.1/6.2 Single-SIM (FI-MNO-05)	FI-6.1/6.2 Single-SIM (FI-MNO-06)	FI-3.1/3.2 Multi-SIM link selection (FI-MNO-05 priority)	FI-3.1/3.2 Multi-SIM link selection (FI-MNO-06 priority)	FI-5.1/5.2 Multi-SIM link aggregation
Mean	76.34	73.75	99.47	88.87	68.29
CI 95%	31 – 477	31 – 389	32 – 674	31 – 575	32 – 356

The performance of the different multi-SIM solutions was also evaluated in agnostic test cases in FI TS using synthetic TCP traffic flows in the UL direction. Overall results comparisons of the single-SIM test cases (TCA-FI-13) versus multi-SIM test cases for link selection mode (TCA-FI-11) and link aggregation mode (TCA-FI-12) highlighted the effectiveness particularly of the link aggregation solution for enhanced throughput performance in the UL direction. This is a useful enhancement for bandwidth intensive UL CAM traffic flows (e.g., Lidar traffic flows described earlier), when considering how contemporary networks are dimensioned with UL having significant bottlenecks (compared to DL direction). However, the throughput gains referred above have to be considered against the increased delay introduced by multi-SIM configuration studied here, particularly for TCP-type traffic when operating in multi-SIM link selection mode. One approach to reduce the end-to-end latency for TCP traffic would have been to reduce the frequency of multi-SIM link (re-)selections. However, this would have had an adverse impact of increased packet loss for UDP traffic flows that sharing the same link. This suggests the need for dynamic traffic-aware link selection criteria for optimal operation of multi-SIM devices.

CN TS

A multi-modem / multi-SIM connectivity solution is considered here as an alternative technology to provide connectivity to the vehicle when it is out of coverage of any 5G network. In the CN TS, UCC/US tests have been performed with multi-SIM connectivity in passive mode, which was defined in D3.7 [1], only to assess the performance of this technology to support the Vehicles Platooning from the Assisted-Cloud US. The CN TS has completed a 2 km expressway in the northern part of Miaoshan, with two NSA networks supported by China Mobile and China Unicom. The network architecture is capable of covering redundant signals of such wide-area road sections in the case of Vehicles Platooning US.

The multi-SIM connectivity in passive mode has been assessed to recover connectivity when 5G communication is lost on the CN TS where two public 5G networks (China Mobile and China Unicom) with limited coverage have been used. The test route configuration is shown in Figure 26.

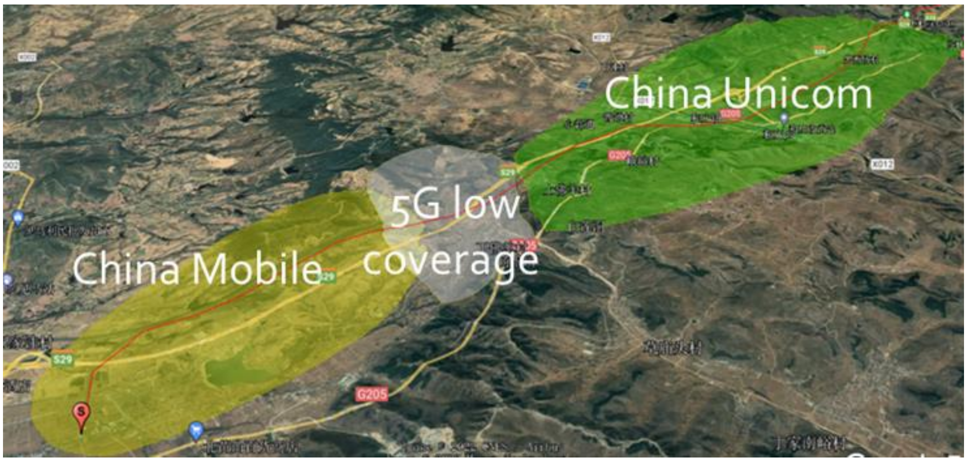


Figure 26: CN TS, simulated 5G low coverage area at Miaoshan expressway to test Platooning use case

To evaluate the performance of the multi-SIM solution with CS_4, Vehicle Platooning US focus on the downlink data rate (TE-KPI-1.1) and packet loss rate (TE-KPI-1.6). Two use cases (CN-2.1 and CN-2.2) were performed as baseline tests and the use case multi-sim solution with link selection mode (CN-2.3) was performed to evaluate the performance of CS_4

The performance of connectivity tests for the leader vehicle are illustrated in Figure 27. The test results show the limited performance of the passive mode to compensate for the lack of cellular network coverage in certain areas, such as when crossing borders. High throughput can be obtained when UE is located within 5G coverage (depicted in orange and red) over 1 Mbps. However, when it arrived at the low coverage area, the evaluation results show limited performance in each test run where the TE-KPI1.2 was observed over the whole low coverage area.

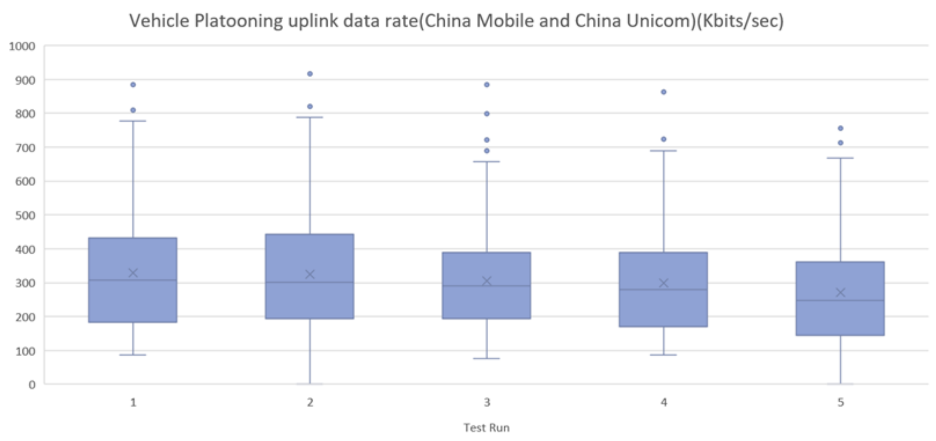


Figure 27: CN TS, downlink throughput performance measured with multi-SIM connectivity passive mode

In addition, the packet loss rates of Platooning formation messages from the MEC server to the platooning leader are shown in Figure 28. In conclusion, an average 9.6% of packet loss was observed with CS_4 but no packet loss in CS_5.

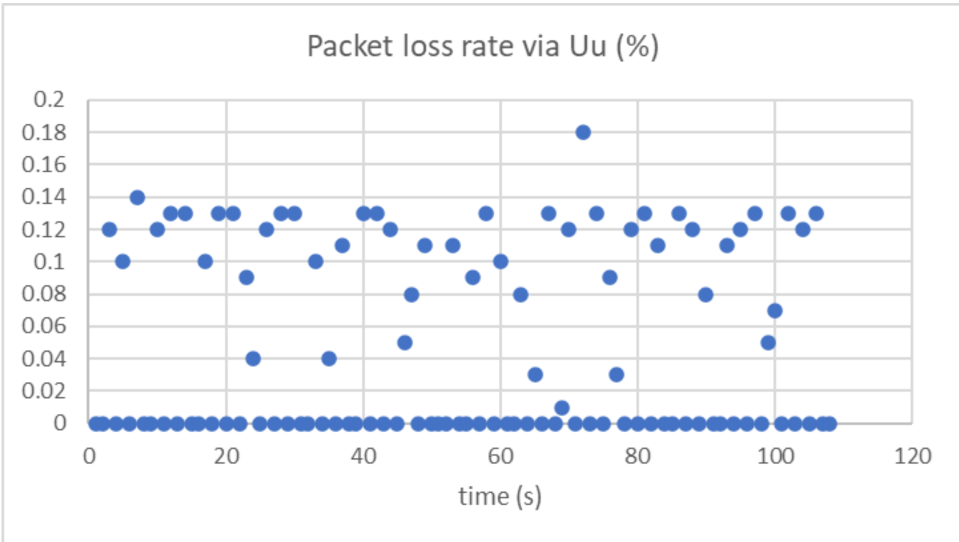


Figure 28: CN TS, packet loss rate via Uu

Solutions to the service continuity issue for V2X applications have been tested using a multi-SIM modem where more than one SIM can be used by a continuous monitoring of communication link (link aggregation).

In the use cases for Remote Driving, two traffic flows are investigated: basic safety message (BSM) and command. The Remote Driving service deployed in the remote-control centre parses the basic safety message and shows vehicle information in the cloud platform. The testing vehicle ran on the route and continuously uploaded BSM via Uu interface and MQTT protocol. The driver at the remote-control centre sends commands to maintain the vehicle running, including acceleration, deceleration and steering. As for our testing configuration, we use single-SIM cases as test baseline and dual-MNO aggregation for the considered trial.

Figure 29 reports the E2E latency time obtained in multi-SIM aggregation mode in comparison with single SIMs with China Mobile and China Unicom. It is clearly visible that this mode offers the highest performances with an average latency of 33.6 ms, with a maximum latency of 98 ms during test runs performed at the local site. Besides, no packet loss has been observed on the CN TS with good network conditions, although packet loss had happened at the CBCs where overlap between the two networks is low.

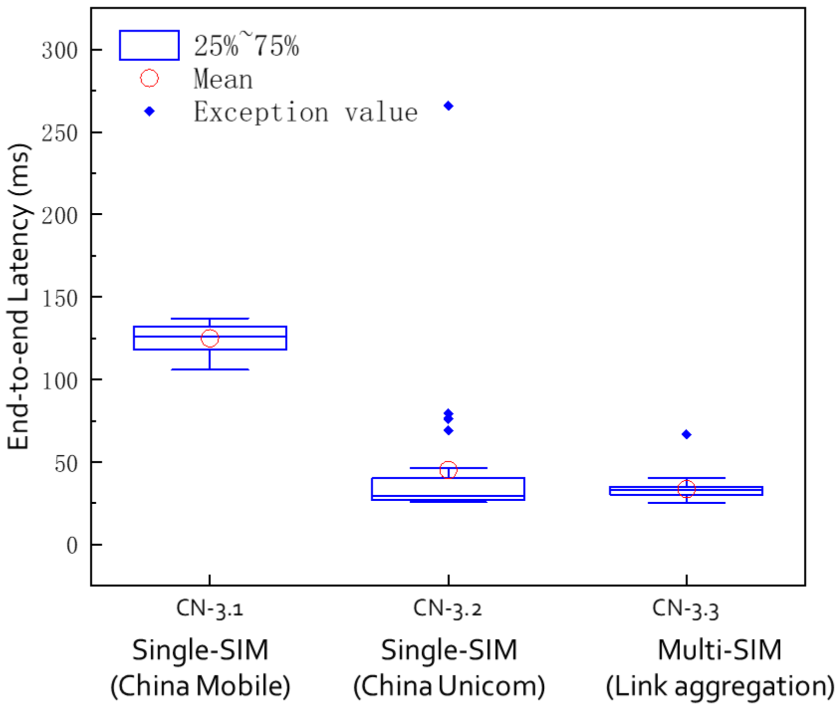


Figure 29: CN TS, E2E latency in ms obtained with different configurations

DE TS

In the DE TS, UCC/US agnostic and specific tests have been performed to evaluate the multi-modem multi-SIM considered solution in passive mode to provide service continuity. In the agnostic test, a ping was sent each 10 ms and the interruption time induced by the switch to the second modem was measured. In all tests, the interruption time starts at the moment when the switch to the second modem is triggered. Regarding the end moment of the interruption time, in the agnostic tests, it is when the OBU is connected through the second modem and the ping is running successfully again, an in the specific tests, when the second MQTT client was connected to the MQTT broker deployed in the second MNO, and it is receiving ITS messages again. Therefore, the results presented for these tests are different, as in the specific test a new MQTT connection is also started.

Regarding the trigger from one modem to the other, it happens in a defined location that is dependent on the signal strength and also on the 5G NR availability in that area. This means that in the location where the first MNO loses its 5G coverage and can only provide LTE signal, the application triggers the signal to change the OBU connection through the second modem, connected to the second MNO which can provide 5G NR connectivity again.

Figure 30 and Table 26 presents the interruption time results measured at the DE TS in a series of agnostic tests where the OBU changes from its first to its second network interface. First, the OBU is connected to the modem with SIM from MNO1 Then the OBU reroutes all the traffic through the modem with SIM from MNO2. The interruption time in these tests was between 50 and 300 milliseconds approximately as shown in Figure 30. These values count the interruption since the first modem connected to MNO1 was switched off, until the second modem connected to MNO2 is already available for the OBU and offers connectivity. The interface switch was performed by the operating system in the computer and took different time depending on actual internal processes (kernel active processes, actual CPU load, USB modem connection, etc.) as presented in Figure 30. These values vary depending on different factors which are: current 5G radio coverage, quality of the second modem used in the moment of the interface switch, Linux kernel modules which induce different delays as shown in the interruption time agnostic test, connection time of a second MQTT client to the second MQTT broker is also variable (visible when comparing Figure 30 with Figure 31).

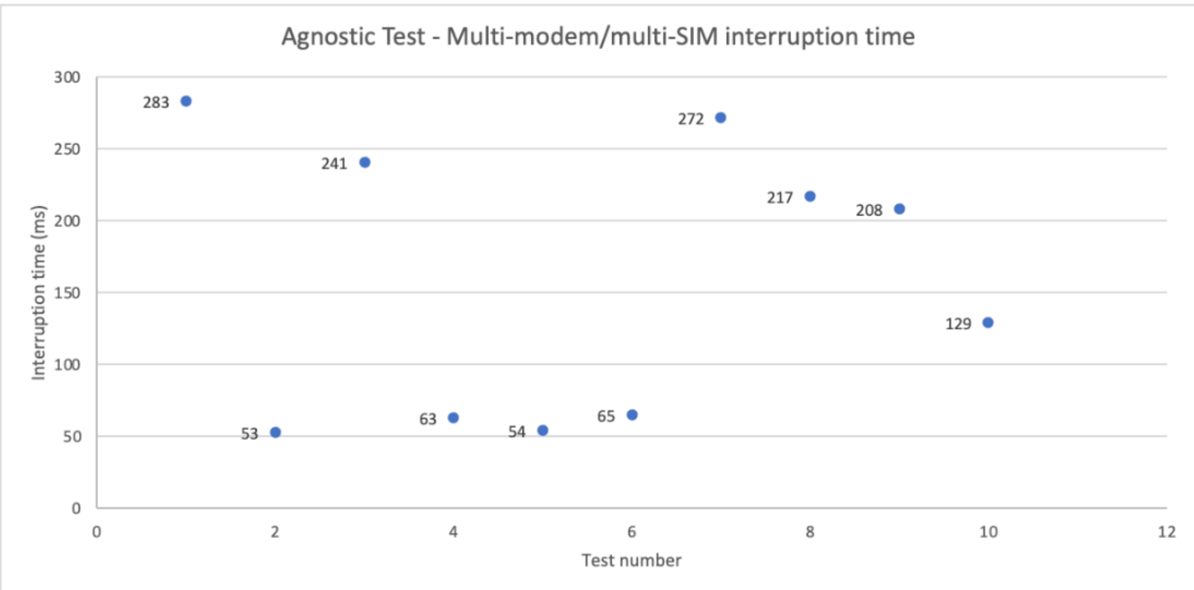


Figure 30: DE TS, multi-modem/multi-SIM interruption time in TCA-DE-06

Table 26: DE TS, multi-modem/multi-SIM interruption time in TCA-DE-06

Test	avg (ms)	median (ms)	std (ms)	max (ms)	min (ms)	CI 95 (ms)	Perc.95 (ms)
TCA-DE-06	158,5	168,5	95,3616	283	53	59,1046	278,05

In Figure 31, the interruption times measured while performing the specific test cases of the eRSU-Assisted Platooning US are presented. The values are much higher (between 1-3 seconds depending on network conditions and MQTT client connection time) than those measured in the agnostic test. The explanation is that the time measured in this case is the interruption since the first modem is switched off, until the second MQTT client connects to the MQTT broker in the second MNO domain and receives the first message from either the infrastructure or other platoon vehicle.

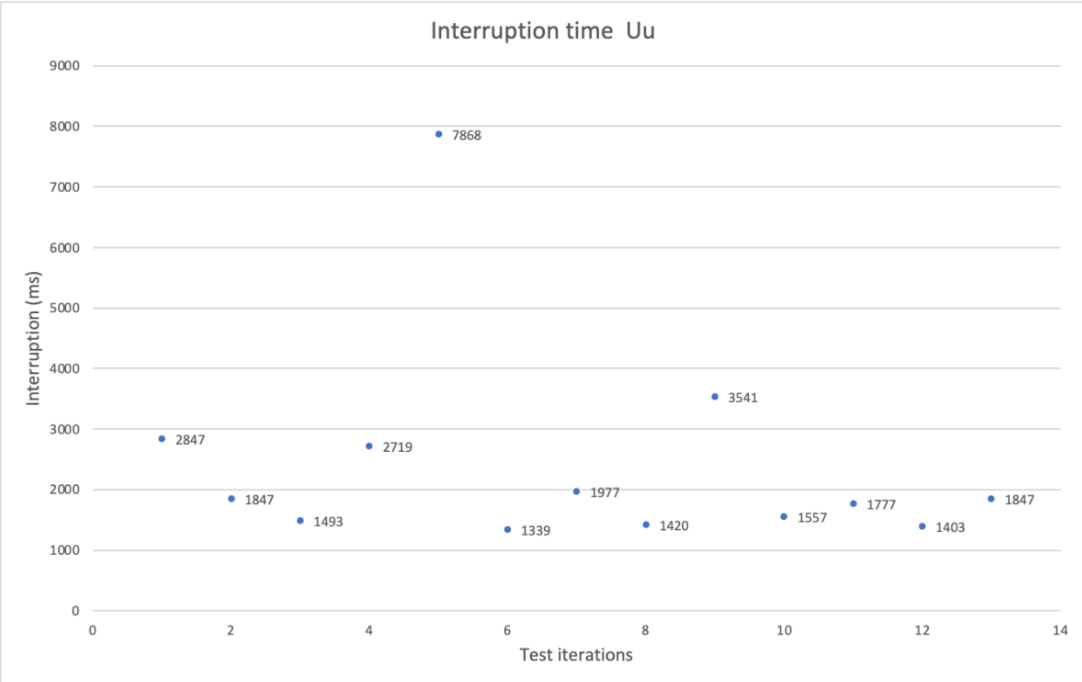


Figure 31: DE TS, multi-modem/multi-SIM interruption time in DE-1.2

Table 27: DE TS, multi-modem/multi-SIM interruption time in DE-1.2

Test	avg (ms)	median (ms)	std (ms)	max (ms)	min (ms)	CI 95 (ms)	Perc.95 (ms)
DE-1.2	2433	1847	1762	7868	1339	958	5272

As a conclusion, a large part of the interruption time observed during the specific tests is generated by the application and the session start-up, after the previous session was suddenly interrupted. The agnostic test results demonstrated that the multi-modem/multi-SIM solution in passive mode provided moderate to low interruption times which can combined with applications specifically optimized for quick session start-up, thus becoming a viable alternative to roaming for some cross-border corridor scenarios. However, the solution requires fine tuning regarding the triggering of the switch between the two modems, which is challenging with respect to the scalable applicability of this solution.

4.5.2. CS_10: MEC service discovery and migration using enhanced DNS support

FI TS

The CS_10 solution was evaluated in the FI TS in the context of the Edge Processing US. Specifically, the test purpose was to analyse the HD-Maps application continuity when vehicle is connected in multi-PLMN environment (two 5G NSA-mode networks) using multi-SIM OBU. The test setup includes two MECs (one associated with each PLMN) providing computational resources for the HD-Maps application. The MEC service discovery and migration will take care of reassigning the MEC when the vehicle traverses in areas with overlapping network coverage and vehicle connectivity switches from one PLMN to another using a multi-SIM OBU working in link selection mode (CS_4) and using a MIP gateway server deployed with a public IP reachable from both networks.

In the trials, the number of PLMN changes (and hence MEC service discovery and migrations operations) varied for different trial runs due to variations in radio channel conditions, network load and so on (see Figure 32). For example, during the 4th round, 4 changes were detected whereas there were up to 15 changes during the first round. Each PLMN change results in an interruption of the video streaming. This includes the delay for MEC service discovery and migration, and the actual delay in resuming video streaming in a new PLMN after the migration.

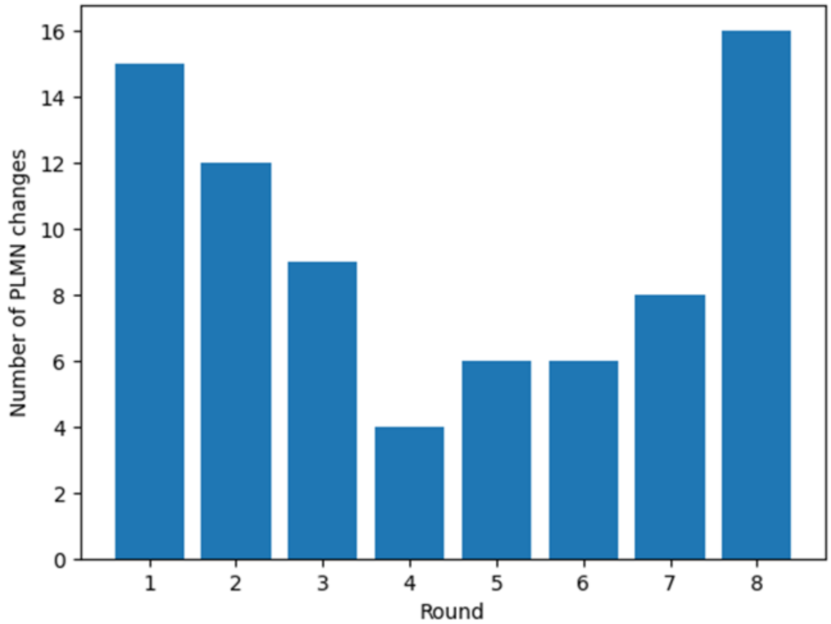


Figure 32: FI TS, number of PLMN changes during each trial round

As noted in Figure 33, the median delay of service discovery is 43 ms. This included (Figure 34) processes of a DNS query from the vehicle to the LDNS, packet forwarding from the LDNS to the authoritative name server, database lookup latency, and a DNS response from the LDNS to the vehicle. The handling and relaying of DNS packets occur over the ethernet within a subnet, which is usually of a latency smaller than 1 ms and a negligible contribution to the overall service discovery and migration delay budget.

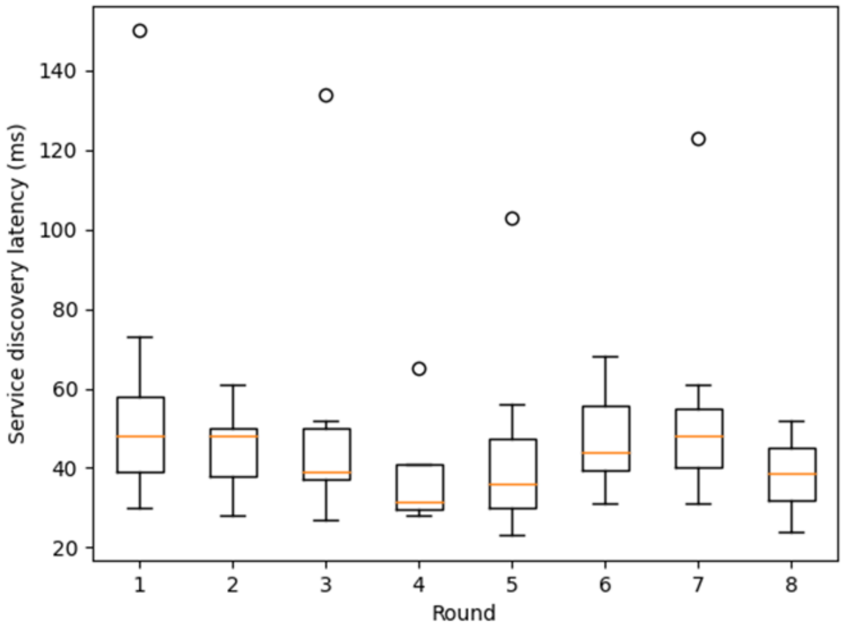


Figure 33 FI TS, service discovery latency on each trial round

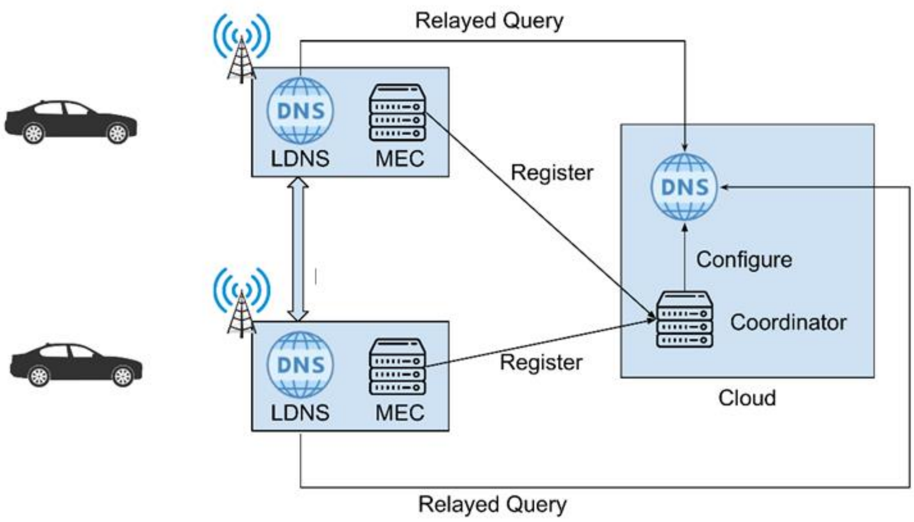


Figure 34: FI TS, service discovery setup based on DNS-approach

On the other hand, video streaming migration latency was calculated as the time period spent between transmitting the last frame when connected to the previous PLMN and transmitting the first frame when connected to the next PLMN. On average, it takes about 4.5 seconds to migrate video streaming to a new MEC (see Figure 35), which is longer than the recommended target value for the HD-Maps application. The migration delay is composed of many factors: 1) the termination delay of the old program, 2) the video streaming handshake delay between the vehicle and the new MEC, 3) service discovery delay, 4) need to send multiple blocking network queries to terminate old MEC programs and start new MEC programs. It means that most of the migration delays are caused by the video streaming application. One reason is that WebRTC takes a few rounds of negotiation between the client and the server for initiating video streaming. Whenever a migration is triggered, WebRTC needs to terminate the existing connection and establish a new one, meaning that the slow start process needs to be started again.

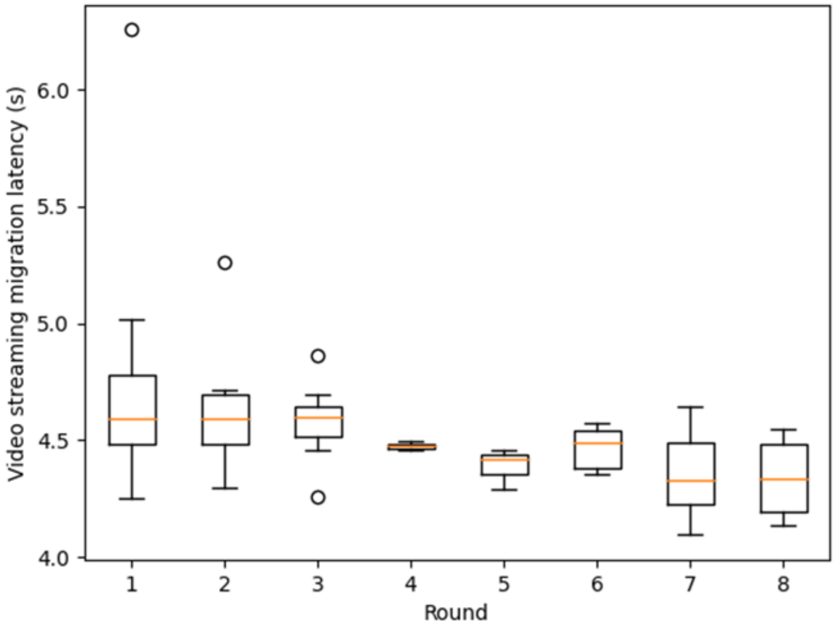


Figure 35: FI TS, video streaming interruption time caused by migration on each trial round

Overall, the service discovery and migration solution demonstrated good reliability even with frequent PLMN changes. However, the interruption time is noted to be higher than required, which can mostly attribute to application-level session stopping and restart procedures during each PLMN change and subsequent MEC migration.

FI TS contribution to ES-PT CBC

Service Discovery was also deployed in ES-PT CBC in the framework of HD-Maps (ES-PT-3.5). The main data flow of this US is the big file with the sensors data that has to be uploaded to the ITS Centre (server behind the MEC) either in ES or PT. FI contribution was oriented towards the re-assignation of the traffic data between the OBU and one of these ITS Centres in a test case in the cross-border with LBO.

Figure 36 is an example of the complete sequence of processes from the handover to the uploading of the sensors file. The test started on the PT side (green area) and the vehicle drives to the ES side (red area). When the vehicle enters the handover (grey area), the modem re-attaches to the ES network (black line) and queries the FI DNS in order to get the IP of the ES ITS Centre (red line). After that, additional time is required at the application layer to restart the FTP process to the ES ITS Centre (blue line) and upload the file (throughput in blue).

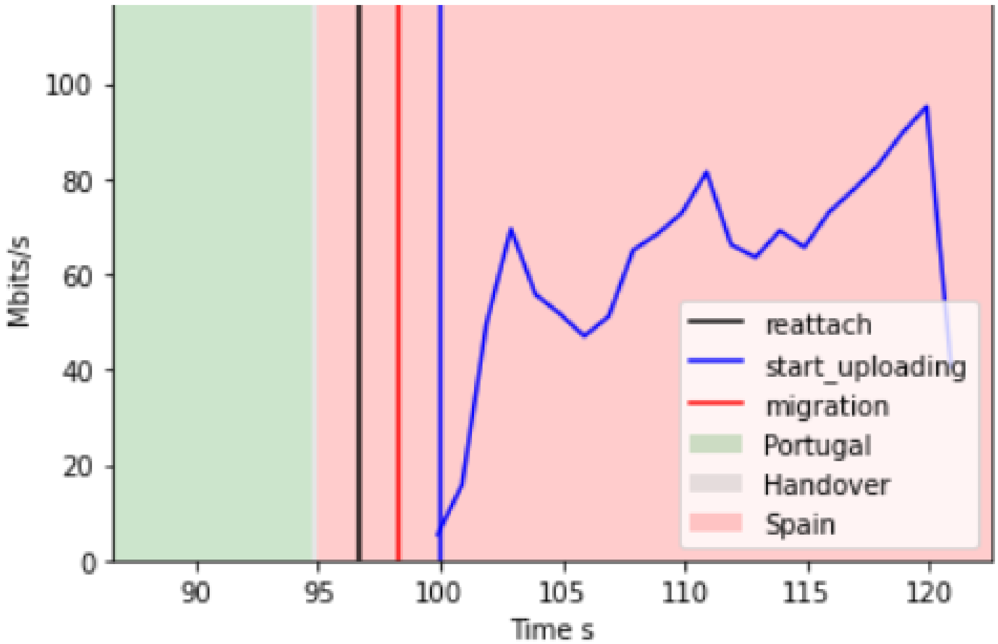


Figure 36: FI TS to ES-PT CBC, sequence of processes between the handover and the uploading of the file with service discovery

Table 28 provides the statistics of the complete service interruption time, from the beginning of the handover to the uploading of the first packet on the PT side, and also the contribution of the DNS migration to this value.

Table 28: FI TS to ES-PT CBC, time differences in Service Discovery for the 3 test runs of ES-PT-3.5

Test	avg (s)	median (s)	stdv (s)	max (s)	min (s)	CI 95 (s)	Perc.95 (s)
Service interruption time	5.7	5.5	1.6	6.4	5.3	5.1-6.4	6.3
DNS migration	1.6	1.6	0.1	1.6	1.4	1.4-1.8	1.7

Service interruption times in ES-PT are in accordance with the ones obtained in FI (on average, 4.5 s in FI and 5.7 s in ES-PT), the variation depends on the distance of the FI server to the ES-PT border and the different architectures of the tests. These high delays do not meet the target values.

4.5.3. CS_13: Double MQTT client

Double MQTT client was tested in ES-PT CBC and DE and CN TS. DE and CN approach is intrinsically subject to the use of the multi-mode multi-SIM solution and there are no specific results to be shown in this chapter.

ES-PT CBC

ES-PT has tested the double MQTT client solution by driving with two vehicles that were sending and receiving CAM messages through the ES and PT MECs with the LBO configuration (ES-PT-2.12 to ES-PT-2.15). Each vehicle had two MQTT clients active, one connected to the network where the vehicle is driving and the other trying to connect to the network on the other side of the border. In this way, during the handover there were two processes in parallel in the OBU in order to save time: the first client was shut down while the other got the connection to the new network.

Figure 37 shows the information logged in the vehicle at the network layer (pcap file of the OBU) during this process in a test from ES to PT (ES-PT-2.14). One can see that the vehicle is firstly connected to the ES MQTT, after the handover, the vehicle is connected to the PT MEC and finally the session with the PT MQTT is established. The time difference between the two MQTT sessions is the service interruption time.

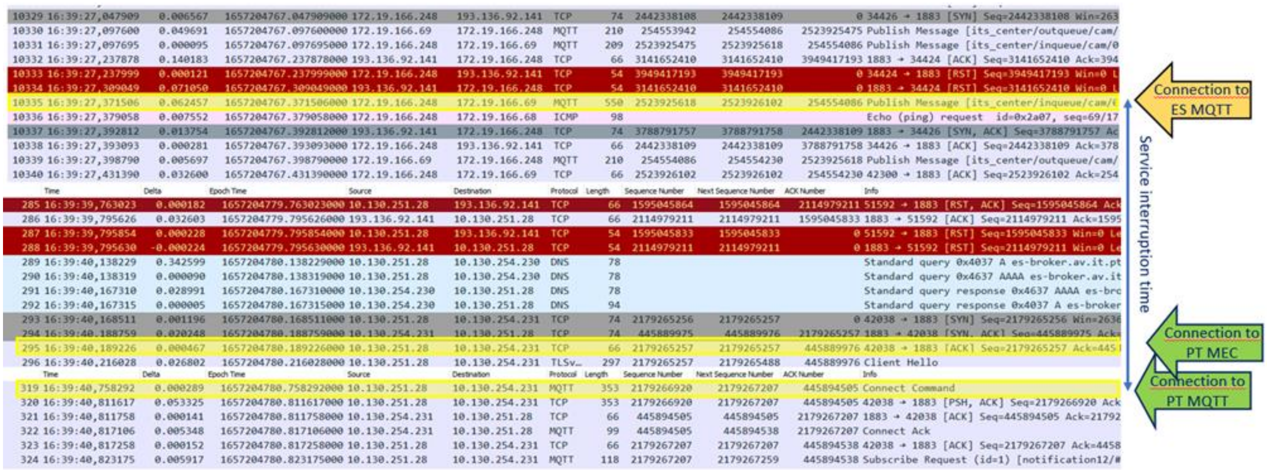


Figure 37: ES-PT CBC, network signalling during the handover process

Table 29 shows the service interruption times in the UL and DL communication for different combinations of driving directions and SIMs. This gap of time without transfer of messages is the sum of the interruption time in LBO, the time-out configuration of the MQTT and the time difference between the connection establishment to the MQTT and the first message sent.

Table 29: ES-PT CBC, service interruption time in LBO configuration with double MQTT client

Test	flow	avg (s)	median (s)	stdv (s)	max (s)	min (s)	CI 95 (ms)	Perc.95 (ms)
PT to ES with ES SIMs (ES-PT-2.12)	UL	13.9	14.0	1.9	16.6	11.3	11.5-16.4	16.2
	DL	11.3	11.7	3.7	15.3	6.8	5.4-17.3	15.0
ES to PT with PT SIMs (ES-PT-2.14)	UL	17.7	14.6	7.0	30.0	13.3	9.1-26.4	27.3
	DL	14.2	14.2	2.2	16.7	10.7	11.5-17.0	16.4

The high interruption times in LBO (see section 4.6.1 for more details) do not allow to show the advantages of the double client MQTT implementation. The modem is consuming too much time to re-attach the network so the improvements on the application side are completely eclipsed.

4.5.4. CS_14: Inter-MEC exchange of data

ES-PT CBC

Advanced Driving US require a copy of the ETSI messages between the two instances of the MQTT broker installed in ES and PT MECs in order to share the information among all the vehicles involved in the CAM functions, the ones driving in ES and the ones driving in PT.

Table 30 shows the latency of these messages at the network layer when traveling through the fibre between them separated by 100 km. Different behaviour is observed in the two directions of the communication between the MQTTs (ES MEC to PT MEC and PT MEC to ES MEC) which can be explained by the different implementation and configuration options in the ES and the PT MQTT brokers as they were deployed by two different partners on the ES (CTAG) and the PT (IT) sides.

Table 30: ES-PT CBC, inter MEC latencies at the network layer in Advanced Driving US

Test	roaming	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI 95 (ms)	Perc.95(ms)
ES MEC to PT MEC (ES-PT-2.10)	HR	3.6	3.6	0.1	5.2	3.3	3.6-3.6	3.7
PT MEC to ES MEC (ES-PT-2.11)	HR	2.2	2.2	0.1	3.6	1.9	2.2-2.2	2.4
PT MEC to ES MEC (ES-PT-2.12)	LBO	1.8	1.6	0.6	4.4	1.1	1.8-1.8	3.2
ES MEC to PT MEC (ES-PT-2.14)	LBO	2.4	2.9	0.8	4.2	1.1	2.4-2.4	3.2

Table 31 makes a comparison of the latency values in UL on the PT side and the ES side when driving from PT to ES in LBO with an ES SIM, meaning that the traffic is routed through the inter-MEC gateway when driving on the PT side. The results reflect this increment in the latency according to the values in Table 30.

Table 31: ES-PT CBC, comparison of latencies at the network layer on the two sides of the cross-border

Test	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI 95 (ms)	Perc.95 (ms)
ES-PT-2.12 (UL to ES MEC)	15.3	15.0	6.9	135	5.0	14.7-15.8	22
ES-PT-2.12 (UL to PT MEC)	19.4	19.0	6.6	130	5.4	19.1-19.6	28.2

NL TS

In the NL TS an inter-MEC exchange is setup between the MECs in the 5G SA networks of TNO and KPN, as sketched in Figure 38. Both networks implement LBO with edge routing. Each MEC has an MQTT server to exchange geo-constrained CAM messages between test vehicles within their home network, as reported in section 4.9.1. In a border crossing situation like Figure 38, where nearby vehicles are connected to different networks, CAM messages need to be exchanged between the MECs of the two networks. This is implemented by federating the two MQTT servers to enable each MQTT server to route traffic to the other. This makes the geo-constrained message exchange completely transparent to connected UEs in the network border area. The federation of MQTT servers has no impact on the reliability and throughput in the 5G RAN. It could however impact the E2E delay. Apart from the application-level configuration of the MQTT servers, this federation is supported by an underlying 11Km optical fiber enabled interconnection of the corresponding physical servers.

Table 32 shows the E2E delays of CPM (CAM messages) exchanged between the UEs in the two test vehicles in the Extended Sensors US. The first row shows the delays in the reference situation in which both test vehicles are connected to the same TNO network and the same MQTT server. The second row shows the delays for the setup of Figure 38 with both vehicles connected to different networks and using the inter-MEC exchange. The average and median delays are similar. The average delay in the reference setup without the inter-MEC exchange is even slightly higher, while the outliers are much larger, than in the setup with the inter-MEC exchange. This is caused by larger variations in the transport elsewhere in the network during the NL-1.3 trials and obviously not an effect of the inter-MEC exchange.

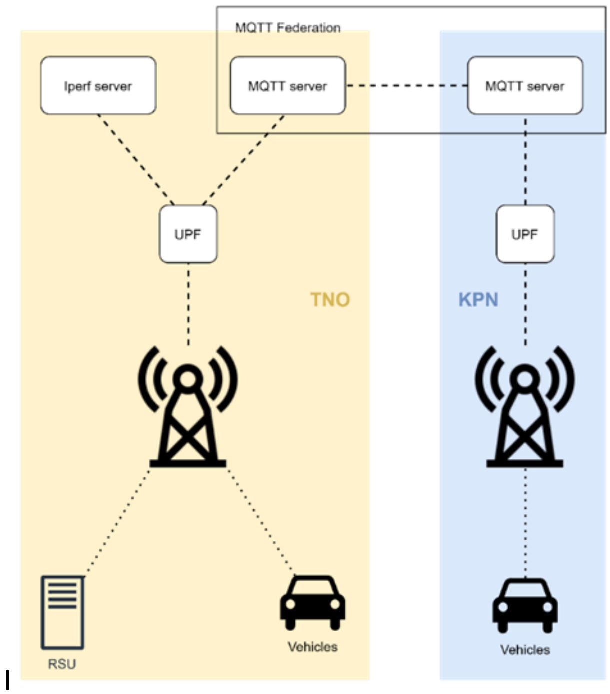


Figure 38: NL TS, inter-MEC exchange setup

It can be concluded that the inter-MEC exchange does not introduce a significant extra delay compared to the edge-routed network and RAN.

Table 32: NL TS, TE-KPI1.3 – E2E latencies with and without inter MEC exchange in the Extended Sensors US

Inter-MEC exchange	Test case	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI 95(ms)	Perc.95(ms)
No	NL-1.3 (section 4.9.1)	23	19	64	1448	13	4.0	24
Yes	NL-1.7 (Figure 38)	20	20	1.8	30	15	0.14	24

DE TS

Figure 39 presents the measurement results for the RTT for synthetic traffic (3 Mbps UL or DL TCP traffic, simulating the ITS messages produced by the infrastructure in the DE TS) sent between the MEC entities that have been used in the DE TS. In total, three different MEC instances were tested, which are the TUB data centre, the MobiledgeX platform located in Berlin's cloudlet, and Amazon Web Services located in Paris. As the figure clearly shows, the best results are obtained for the inter-MEC connection of AWS and MobiledgeX, which are both commercial products. On the other hand, when the connection is between TUB and any of the other two MECs, the RTT is slightly higher, which may be due to large-scale campus network at TUB, connected to a national research network backbone and shared among a large user base.

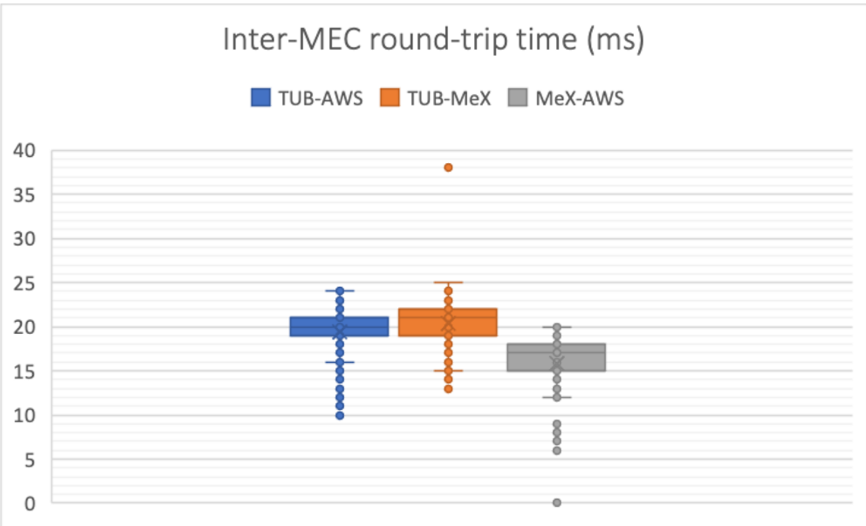


Figure 39: DE TS, inter-MEC broker latency

Figure 40 presents the measurement results for the RTT for synthetic traffic sent between the road side units deployed and the MEC entities that have been introduced in D3.7 [1] for the DE TS. This measurement is relevant because all the EDM data, which is produced by the infrastructure co-located with the RSUs, is sent from the eRSU to the MECs, causing extra delays to the overall E2E-latency. The interconnection from the eRSU with the two commercial MECs, AWS and MobiledgeX, is done via 5G Uu interface, thanks to a 5G modem integrated in the eRSU. At the same time, the eRSU is connected via ethernet to TUB data centre over the campus network. It is clearly visible that the 5G RTT measurements are five times higher compared to connectivity via ethernet.

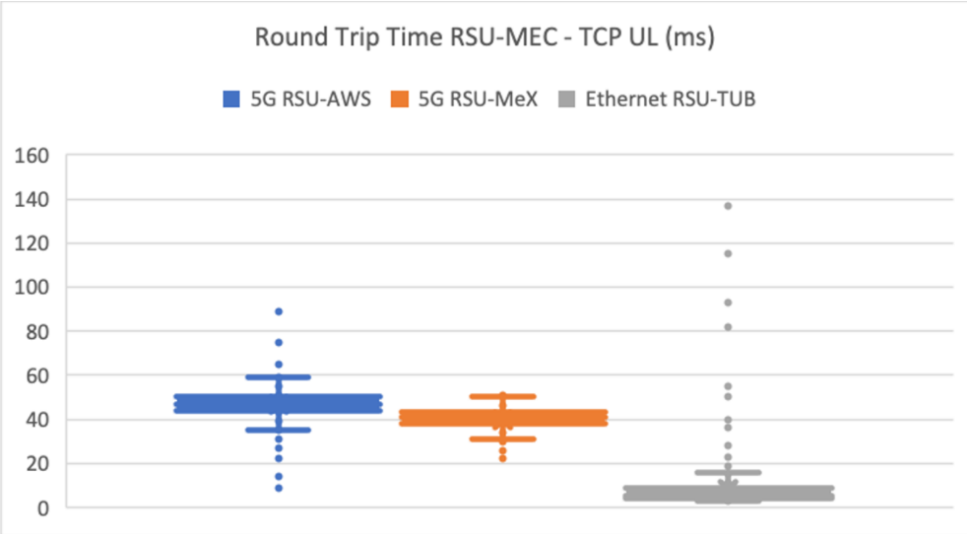


Figure 40: DE TS, eRSU - MEC broker latency

FR TS

Advanced Driving tests which consist in having a connected vehicle exchanging C-ITS messages with a MEC server depending on its geographical location have been carried out by FR TS participants at the ES-PT CBC. During these tests (TCS-FR-1.5), a connected vehicle is driving across the border between ES and PT and changing connection to V2X servers installed in the MEC deployed in both countries.

First, average throughput of 0.014 Mbps and average latency of 22.2 ms have been observed during the communication between multiple vehicles and a RSU. As illustrated in Figure 41, the connected vehicle driving across the border is able to correctly decode both CAM and CPM having average data rate of 1400 bps and 800 bps respectively. Also, the results show that the UE could detect the border crossing based on its ego location and switch from one V2X server to another one as a destination for the exchange of V2X messages.

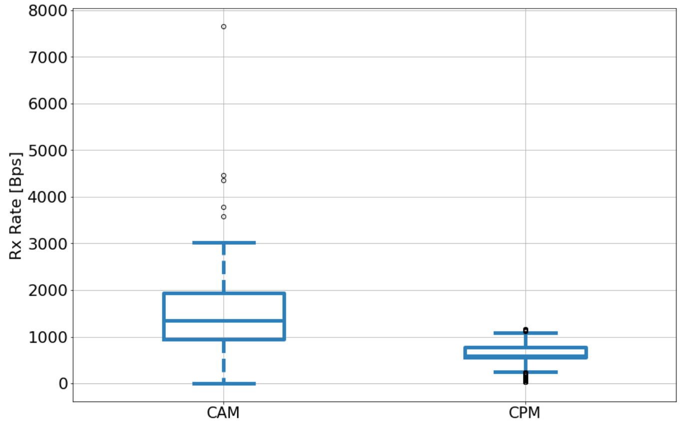


Figure 41: FR TS, data rate of received V2X messages during tests at the border crossing

During the border crossing, the vehicle could change the destination of V2X message to send to the relevant MEC and could receive data from other vehicles, with good performances in inter-MEC communication.

CN TS

In the CN TS, the "interconnection" of MECs was realized within a software-defined network via the internet. MECs were deployed over two commercial mobile network operators, China Mobile and chine Unicom. As sketched in Figure 42, the web server deployed at the MEC receives the basic safety message (BSM) that the vehicle continuously reports. A private 5G SA/NSA network supported by China Mobile and a public NSA network supported by China Unicom were deployed. Each MEC has an MQTT server to exchange BSM messages between test vehicles within their serviced network. When the vehicle moves to the roaming area, the dominant cross-border issue is session and service continuity as the switching event occurred between MNO1 and MNO2. The use cases adopted multi-modem / multi-SIM solution to maintain dual TCP sessions simultaneously, and double MQTT client to provide redundancy of MQTT sessions.

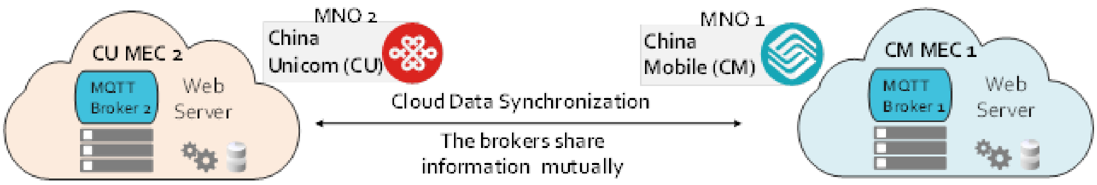


Figure 42: CN TS inter-MEC exchange setup

To verify the performance of E2E latency with two network settings (SA/NSA), two connected vehicles were used, driving across, the pre-set location where a switching event occurs between MNO1 and MNO2 establishing connections to MQTT brokers installed in different MNO servers. Figure 43 shows the E2E delays of BSM messages exchanged between the UEs in the two test vehicles in the Cloud-Assisted Advanced Driving. The boxplot figure shows the delays with both vehicles connected to different networks: NSA (CN-1.2: China Mobile with NSA, China Unicom with NSA) and SA (CN-1.3: China Mobile with SA, China Unicom with NSA) network. The average and median delays in the SA network are lower than the one obtained in the tests in the NSA network, while the outliers are much more dispersed than in the setup with NSA. The private network with self-established components is autonomous and controllable. Under the requirements of comprehensive consideration of delay and reliability, an optimal route path had been calculated in terms of the known deployment of private network sites. The designed route path in the SA network reduces latency caused by the uncertain route between the UE and target server under NSA. The results also show the necessity of tuning the private network finely to reduce delay jitter in the SA network.

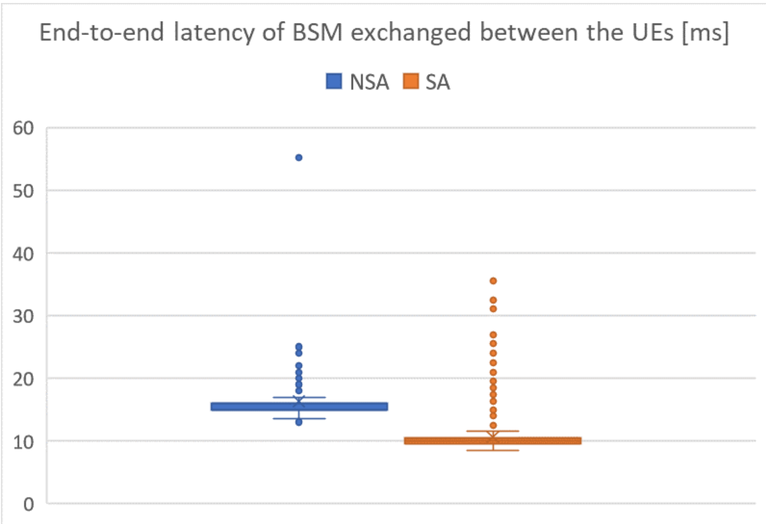


Figure 43: CN TS, E2E latencies with NSA and SA network in the Cloud-Assisted Advanced Driving

4.5.5. Conclusions

The multi-modem multi-SIM solution in passive mode and with link aggregation was tested in four TS with very similar conclusions. The link aggregation mode (CS_5) provides the highest performance for service continuity, throughput and reliability as it is maintaining in parallel the two sessions with both SIMs. On the contrary, the passive (link selection) mode (CS_4) is prone to increased latencies and service disruption due to frequent link (re-)selection events, presenting the dependence of the solution on the optimization of the link selection algorithm.

The MEC service discovery proved to be a feasible solution when it is necessary to migrate the traffic data to a new server but considering that the time for the DNS query depends on the distance to the DNS server.

The double MQTT client could not showcase its potential because the long LBO interruption times hide this implementation on the application side.

The inter-MEC communications, both the commercial ones and the direct interconnections, are feasible features that add very few ms to the E2E latency.

All these solutions improved the service continuity but, at the same time, are strongly affected by added latencies from the application side, which need to be optimised to shorten it.

4.6. XBI_6: Data Routing

This cross-border issue explores the impact of HR or LBO roaming configurations on network/service performance, in the context of inter-PLMN handovers. HR maintains the session to the home network whereas LBO changes it to the visited one in order to minimize the latency. As such, HR is expected to yield better mobility interruption times, compared to LBO, however, presenting sub-optimal, latency-prone routing i.e., traffic always passes through the home gateway (at the home PLMN). In this context, the evaluation focused on assessing/quantifying this performance trade-off in the available network deployments. It is noted that the overall assessment depends also on aspects related to handover related interruptions; these has been discussed in Sections 4.1 and 4.2 (so as to focus on the individual technical aspects of this composite setup and corresponding performance evaluation).Tests were performed in both CBCs (Table 33).

Table 33: Summary of UCC/US where XBI_6 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_16 LBO NSA	ES-PT	Advanced Driving	Overtaking	ES-PT-2.12 to ES-PT-2.15
		Extended Sensors	HD-Maps Vehicle	ES-PT-3.5
	GR-TR	Vehicle Platooning	SeeWhatISee	
		Extended Sensors	Assisted Border Crossing	GR-TR-4.4, GR-TR-7.4
CS_17 HR NSA	ES-PT	Advanced Driving	Lane Merge	ES-PT-1.2 and ES-PT-1.4
			Overtaking	ES-PT-2.2 to ES-PT-2.11
			Cooperative Automated	ES-PT-5.6 and ES-PT-5.7
		Extended Sensors	HD-Maps Vehicle	ES-PT-3.2 and ES-PT-3.4
		Remote Driving	Remote Control Crossing	ES-PT-6.3, ES-PT-6.6 and ES-PT-6.8
		QoS	Media Public Transport	ES-PT-7.1 and ES-PT-7.3
	GR-TR	Vehicle Platooning	SeeWhatISee	GR-TR-11.1
		Extended Sensors	Assisted Border Crossing	GR-TR-4.1, GR-TR-4.2, GR-TR-7.1, GR-TR-7.2

4.6.1. Comparison of CS_16 (LBO NSA) and CS_17 (HR NSA)

ES-PT CBC

The direct interconnection deployed in ES-PT is especially oriented towards the test cases that require minimal values of latency and it is affected by the roaming configuration deployed in the network. Figure 44 schematizes the network architecture with particular focus on the path followed by the data in HR and LBO, when the vehicle is in the home network and in the visited one.

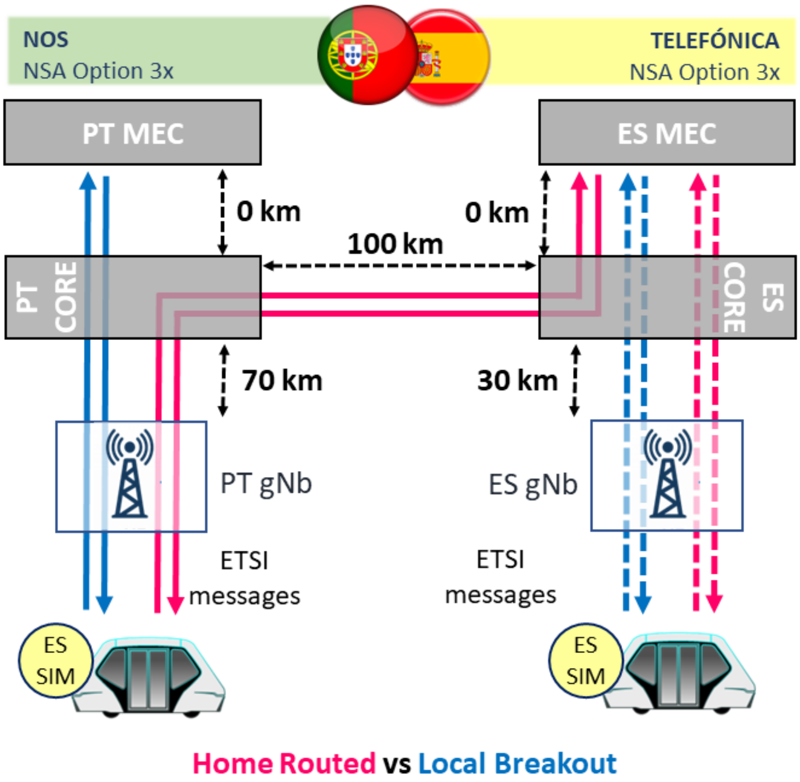


Figure 44: ES-PT CBC, network architecture in ES-PT comparing the data paths in HR and LBO

First tests about the latency were performed in an UCC/US-agnostic way by means of a ping when crossing from ES to PT (before, during and after the handover), and vice versa, in the two locations of the trials (New Bridge and Old Bridge). The first conclusion on these results (Table 34) is about the comparison between HR and LBO configurations, latency values in LBO are shorter because the vehicles are always connected to the closest MEC. This result is comparable to the one for HR when connecting to the home or the visited networks, the extra path to get the core of the home network when driving in the visited country adds an additional latency, although, in this case it is not very impactful on the latencies because of the shorter distances. This effect of the distance between the location of the trials and the MECs is also illustrated by means of the minimum latency in HR being shorter when using the ES SIM than the PT one, as the ES MEC is 70 km closer than the PT one. No meaningful differences between the tests in the two locations were found, meaning that the vehicle speed is not affecting the latency.

Table 34: ES-PT CBC, E2E latency with ping tests executed with HR/LBO, in both directions and both locations

CS	Driving direction	Location	avg (ms)	median (ms)	std (ms)	max (ms)	min (ms)	Perc.95(ms)
CS_17 (HR) TCA-GEN-33	ES to PT	New Bridge	39.7	25.1	54.1	835	13	102.1
	PT SIM	Old Bridge	31.1	29.4	13.7	220	12.2	57.3
	PT to ES	New Bridge	37.3	29.0	52.0	915	9.6	54.4
	ES SIM	Old Bridge	27.1	25.2	8.9	151	10.2	43.1
CS_16 (LBO) TCA-GEN-34	ES to PT	New Bridge	26.2	22.2	25.0	459	8.5	68.7
	PT SIM	Old Bridge	25.8	23.2	25.8	367	8.4	68.5
	PT to ES	New Bridge	33.0	27.6	44.6	476	9.4	90.6
	ES SIM	Old Bridge	31.0	26.3	26.4	260	9.4	85.6

The tests performed in the context of the Advance Driving US, where ES and PT MQTTs are directly hosted in the ES and PT MECs, revealed comparable results.

Table 35 shows the latency values in UL and DL when driving from PT to ES with two vehicles sending/receiving CAM messages with ES SIMs in HR (ES-PT-2.10) and LBO (ES-PT-2.12). Latency values are shorter with LBO, because the messages do not go through the interconnection when the vehicle is in the V-PLMN, as it can be checked compared the latencies against the ES and the PT MECs.

Table 35: ES-PT CBC, comparison of network latencies in HR and LBO driving from PT to ES with ES SIMs

CS/Test	Flow direction	avg (ms)	median (ms)	std (ms)	max (ms)	min (ms)	CI95(ms)	Perc.95(ms)
CS_17 (HR) ES-PT-2.10	UL	22.2	18.8	20.7	420	2.3	21.7-22.7	39.5
	DL	14.7	10.3	19.9	473	5.4	14.4-15.1	56.8
	E2E	60.7	60.5	35.0	529	17.7	58.7-62.8	118.8
CS_16 (LBO) ES-PT-2.12	UL	18.7	18.9	6.8	135	4.9	18.4-18.9	27.8
	UL ES MEC	15.2	15.0	6.9	135	4.9	14.7-15.8	22.0
	UL PT MEC	19.4	19.0	6.6	130	5.4	19.1-19.6	28.2
	DL	10.1	7.1	13.7	297	5.7	9.7-10.5	20.9
	DL ES MEC	7.4	6.7	2.4	37.6	5.7	7.2-7.5	10.5
	DL PT MEC	11.0	7.2	15.5	297	5.8	10.5-11.5	39.3
	E2E	40.6	32.9	27.1	317	14.2	39.5-41.8	94.7

In addition to the previous comparison between both roaming options, the agnostic tests performed in both bridges produced a detailed insight regarding the most significant performance parameters with HR NSA configuration, both in DL and UL directions, which are summarized in the following tables. The tables show one way delay (OWD) measurements moving from ES to PT, using a terminal with a TELEFÓNICA SIM card.

The end point points are located in the terminal and the MEC server in ES. To measure the OWD a continuous low throughput UDP stream is sent from the MEC to the terminal (DL) or from the terminal to the MEC server (UL).

Table 36: ES-PT CBC, results obtained for the TE-KPI1.3-E2E Latency (ms) in the Old Bridge (UDP protocol)

Test case	avg	Median	Stdv	Max	Min	CI 95%	Perc.95%	samples
UDP DL no load	57,06	50,25	48,82	424,56	8,69	3.34	127,20	821
UDP DL loaded	31,98	16,00	58,17	803,00	6,00	3,95	57,45	832
UDP UL no load	323,14	38,61	890,31	6944,23	14,93	57.07	1842,97	935
UDP UL loaded	47,10	28,00	121,16	2206,00	10,00	4,59	59,15	2678

Table 37: ES-PT CBC, results obtained for the TE-KPI1.3-E2E Latency (ms) in the New Bridge (UDP protocol)

Test case	avg	median	stdv	Max	Min	CI 95%	Perc.95%	samples
UDP DL no load	53,75	38,97	63,26	860,73	6,19	2,91	176,24	1813
UDP DL loaded	15,51	11,00	10,63	83,00	8,00	0.93	43,00	499
UDP UL no load	344,74	47,02	765,63	7254,58	16,61	47.15	991,58	1013
UDP UL loaded	337,41	49,00	1028,27	9282,00	15,00	108,19	1704,00	347

Table 36 and Table 37 show slightly shorter latency times (one-way-delay) results in the New Bridge compared to the Old Bridge maybe due to the shorter distance to the base station in the New Bridge. It can also be observed that the UL latencies are significantly higher compared to the DL latencies, as it happens in almost all cellular networks. Measured results show that loaded networks (3 devices transmitting with the same configuration used with one single device) do not seem to worsen the latency results compared to networks without load. For the tests the load scenario used was to have more than one terminal transmitting at the same time. Because of the low throughput used in the UDP stream and the limited number of simultaneous transmitting terminals (2 extra terminals) no degradation is expected due to the load.

Degradation in UDP transmission will most likely show up as packet loss (Table 38 and Table 39) in congested networks. In case of TCP transmission degradation in congested networks will result throughput reduction to each terminal until the maximum capacity is reached. The measurements in loaded and no loaded condition were taken at different times and the network performance may be influenced by the co-existence with real user traffic in the radio nodes on the ES network as its resources are shared with the commercial one.

Table 38: ES-PT CBC, results obtained for the TE-KPI1.6-Reliability (%) in the Old bridge (UDP protocol)

Test case	avg	median	stdv	max	min	CI 95	Perc.95%	samples
UDP DL no load	99,37	100,00	49,23	100,00	74,50	0.18	100,00	822
UDP DL loaded	68,96	100,00	45,94	100,00	0,00	2.61	100,00	1192
UDP UL no load	97,29	100,00	13,77	100,00	0,00	0.91	100,00	1532
UDP UL loaded	93,85	100,00	24,00	100,00	0,00	0,88	100,00	2861

Table 39: ES-PT CBC, results obtained for the TE-KPI1.6-Reliability (%) in the New bridge (UDP protocol)

Test case	avg	median	stdv	max	min	CI 95	Perc.95%	samples
UDP DL no load	97,61	100,00	49,09	100,00	0,00	0.42	100,00	1816
UDP DL loaded	86,24	100,00	34,37	100,00	0,00	2,80	100,00	578
UDP UL no load	99,67	100,00	1,94	100,00	81,50	0.53	100,00	310
UDP UL loaded	99,43	100,00	9,23	100,00	0,00	0.97	100,00	349

The agnostic tests show a very good performance of the network in terms of reliability in both bridges with minor degradation, slightly higher in the Old Bridge

NL TS contribution to ES-PT CBC

The Collision Avoidance application from the NL test site was also tested in the ES-PT cross border test site in an overtaking scenario with local test vehicles. This has been tested in several scenarios with single and multiple networks. Most interesting is the cross-border scenario in a HR configuration on the public road (test case NL-2.43) in which all OBUs have to make a hand over between the ES and PT networks. Table 40 shows the E2E latencies between OBUs. While connected to the Portuguese network, the OBUs are routed to the MEC and the MCS application on the MEC in the Spanish network. Consequently, the E2E latency increases by about 14 msec (on average) when vehicles are in the PT network area compared to the ES network.

Table 40: NL TS to ES-PT CBC, TE-KPI1.3 – E2E latencies in msec for geo-constrained messages exchange in cross-border scenarios for the Collision Avoidance US in the ES-PT CBC in a HR configuration

Border Crossing	Network(s)		avg	median	stdv	max	min	CI 95	Perc.95
Yes	ES-PT with handover								
	Both OBUs in ES	5G NSA	53	46	31	219	24	49.8-55.2	152
	Both OBUs in PT	5G NSA	67	59	30	300	23	66.2-68.5	109

Note that the driving scenario in the ES-PT tests differs from the scenarios in the NL TS in section 4.9.1, and that the MCM messages are larger resulting in a data rate of 210 kbps. Note also that latency is higher because the ES-PT site uses NSA networks as opposed to the SA test networks in the NL TS site. Also note that the modem used in the ES-PT CBC tests (Xiaomi phone) differed from the modem used in the NL TS (Netgear Nighthawk). This was because the modem used in one test site did not operate well in the other test site.

GR-TR CBC

The results mentioned in the following paragraphs are related to the Assisted Zero-Touch Border Crossing case. The rationale of this XBI is to evaluate the routing of the data once the radio handover has happened. However, it is important also to have some evaluation on the application level experienced interruption time. Specifically, measurements reported from the application side are logged using a COSMOTE (GR network) SIM card, and represent the interruption time experienced by the OBU when changing PLMNs (from home PLMN to visited PLMN and vice versa). Different trials were performed with a cloud server and two edge servers, one located on the GR side of the borders, and one located at the TR side of the borders. The detailed measurements for all the relevant testcases are reported in the Appendix.

Table 41: GR-TR CBC, application level experienced mobility interruption time with HR

Interconnection	Test case	samples	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI95 (ms)	Perc.95 (ms)
Cloud Server - HR (CS_17)									
Public Internet (CS_7)	GR-TR-4.1 GR-TR-7.1	8	710	742.19	162.69	883.57	307	[65,855]	858
Direct Interconnection (CS_8)	GR-TR-4.2 GR-TR-4.4 GR-TR-7.2 GR-TR-7.4	4	767	884.48	241.05	893.73	405.57	[383,1150]	892
Edge Server - HR (CS_17)									
Public Internet (CS_7)	GR-TR-4.1 GR-TR-7.1	8	867	842.36	72.57	1026.5	798.16	[806,928]	988
Direct Interconnection (CS_8)	GR-TR-4.2 GR-TR-4.4 GR-TR-7.2 GR-TR-7.4	4	774	831.37	181.33	910.09	526.28	[486,1063]	909

Table 42: GR-TR CBC, application level experienced mobility interruption time with LBO

Interconnection	test case	samples	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI95 (ms)	Perc.95 (ms)
Edge Server – LBO (CS_16)									
Direct Interconnection (CS_8)	GR-TR-4.2 GR-TR-4.4 GR-TR-7.2 GR-TR-7.4	4	4542	4453	186.95	4822	4440	[4244,4839]	4768

From Table 41, it can be observed that for the HR data routing (CS_17) the mobility interruption time does not differ significantly whether a cloud server or edge servers are used, and the average interruption time remains between 710 ms – 867 ms. These results are obviously not satisfactory for stringent CAM applications. For instance, an autonomous stopping process of the truck, in the event a custom agent is detected in its path, would under-perform due to this interruption time. Such an interruption time would jeopardize the performance of the autonomous stopping directive if it occurred right at the moment of handover, as it would add an additional 10 m (approximately) to the stopping distance of any truck driving at 50 km/h. Nevertheless, in the presence of the considerably lower mobility interruption times reported in Section 4.1, for the HR setup, further investigations are deemed necessary so as to gain a better understanding of the application implementation specificities that are potentially associated with the above deviating results.

When the LBO data routing is used (Table 42), the interruption time experienced by the OBU is unacceptably high (close to 4.5 seconds), due to the OBU-triggered PGW change, which requires the reset of the OBU's connection manager. The rationale of this was to show also the importance of interruption time which is crucial especially in cross-border environments. All measurements were performed using a COSMOTE SIM card and handovers were performed in both directions of traffic, i.e., from the home PLMN to the visited PLMN and from the visited PLMN to the home PLM.

Regarding the following paragraphs, the measurements reported from the application side are logged using a COSMOTE (GR network) SIM card, and represent the E2E latency (RTT) experienced between the OBU and the respective server. Different trials were performed with a cloud server and two edge servers, one located on the GR side of the borders and the other located at the TR side of the borders. The detailed measurements for all the relevant testcases are reported in the Appendix.

Table 43 depicts the average E2E latency from an application perspective. The results are presented separately for the case of the cloud server scenarios and the edge server scenarios. All measurements were performed using a COSMOTE SIM card and handovers were performed in both directions of traffic, i.e., from the home PLMN to the visited PLMN and from the visited PLMN to the home PLMN.

Table 43: GR-TR CBC, average E2E latency experienced from OBU to server and back for LBO configuration

Server	Test case	samples	avg (ms)	median (ms)	stdv (ms)	max (ms)	min (ms)	CI95(ms)	Perc.95(ms)
Cloud	GR-TR-4.2, GR-TR-4.4 GR-TR-7.2, GR-TR-7.4	23528	171	135.77	116.06	1906	71.27	N/A	345
GR Edge	GR-TR-4.2, GR-TR-4.4 GR-TR-7.2, GR-TR-7.4	2848	78.4	67.11	42.75	1050	35.96	N/A	140
TR Edge	GR-TR-4.2, GR-TR-4.4 GR-TR-7.2, GR-TR-7.4	2522	119.6	109.64	49.98	1316	69.75	N/A	177

To further investigate the cause of this unexpected behaviour for the case of the cloud server deployment, an analysis based on the serving network was performed, and the results are shown in Table 44. It can be observed that even though a COSMOTE SIM card has been used for these measurements the experienced latency is actually higher on the COSMOTE network side than the TURKCELL network. This leads to the conclusion that due to the fact that the COSMOTE gNB is about 3.2 km away from the trial site and there is no LoS, the quality of the signal was significantly deteriorated on the day of the measurement leading to a poor performance (while the TURKCELL gNB is actually quite close to the trial site and has LoS). Moreover, the circumstances at the GR side of the GR-TR border were very dynamic, with constant change in the number of trucks waiting in line to go through customs, and in some cases a "steel wall of trucks" would be formed between the COSMOTE gNB and the trial site, further deteriorating the received signal. The measurements shown in Table 44 are thus affected by the poor environmental and channel conditions of the day of the measurement.

Table 44: GR-TR CBC, average E2E latency analysis per serving network (LBO)

	avg (ms)
Total E2E latency	171
COSMOTE (GR) E2E	206
TURKCELL (TR) E2E	161

By observing the edge server measurements from Table 44 (performed on a different time of the day) the positive effects of the LBO configuration on the experienced E2E latency become clear. In the case of the GR edge server the performance with the HR configuration was already extremely good, thus the improvement with LBO is minimal (approximately 5% improvement). As a COSMOTE SIM card was used, the data routing between the OBU and the GR edge server remains pretty straightforward in both HR and LBO cases (home PLMN). The big difference is observed when roaming into TR with a COSMOTE SIM card, as the experienced E2E latency drops 55% when using the LBO configuration, as the data no longer need to travel back to the COSMOTE network before reaching the designated server.

These results confirm, from an application point of view, that the LBO configuration can indeed significantly improve the experienced E2E latency for CAM applications. However, looking at the results regarding the interruption time of LBO, it is still not suitable for cross-border operation with 5G NSA networks.

The 5G Platooning tests were performed on the GR-TR border area bridges that are located in the buffer zone between two countries. HR NSA configuration was used during these tests on both DL and UL directions.

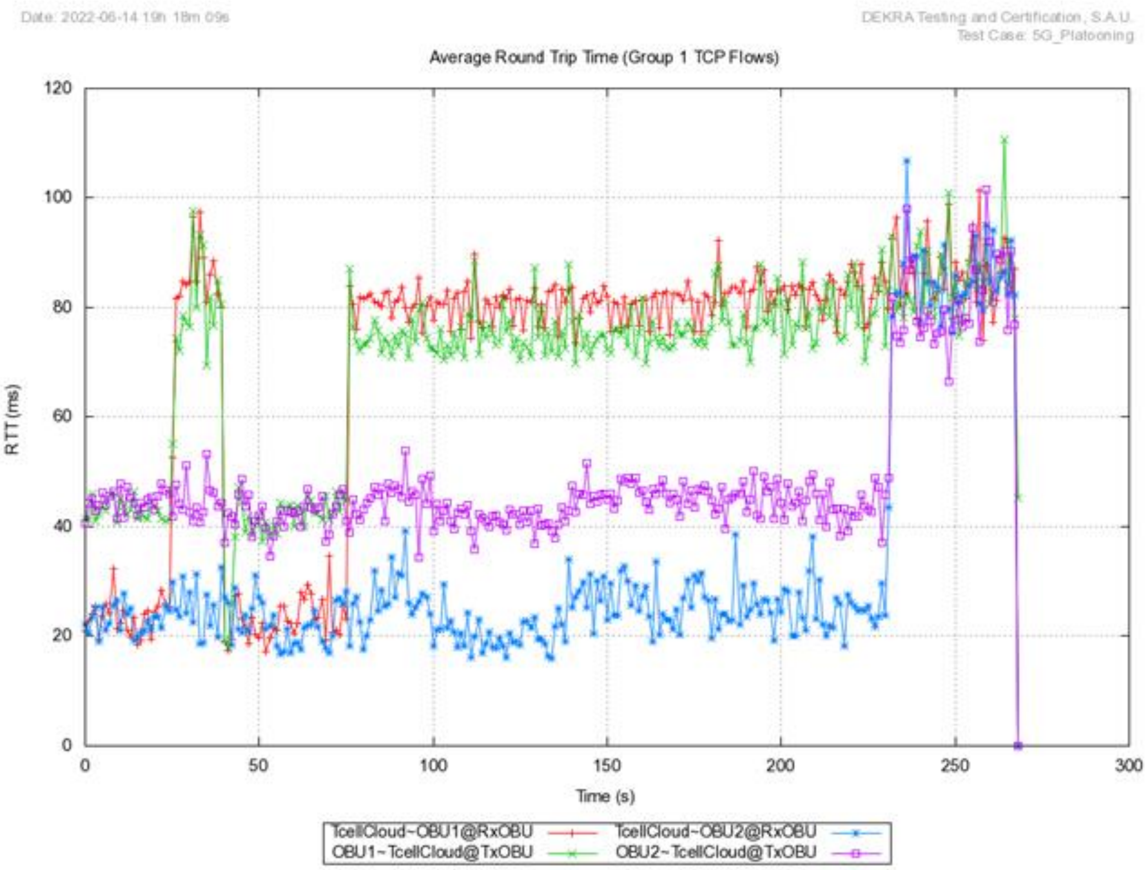


Figure 45: GR-TR CBC

In this US, TCP RTT is measured, since MQTT broker and client communicates through TCP protocol. As it can be seen in Figure 45 and Table 45, RTT are less than 100ms in average for all routes.

Table 45: GR-TR CBC

	avg (ms)
Cloud to OBU1	68.85
OBU1 to Cloud	69.67
Cloud to OBU2	32.37
OBU2 to Cloud	48.98

According to measurement results, we saw that reliability of the 5G connection between OBUs and Cloud is 100%. This result would be differed if exchanged message rate was higher than kbytes.

4.6.2. Conclusions

ES-PT and GR-TR results appear to be highly consistent demonstrating again the reproducibility of results between both CBCs when using different network architectures and data flows in the test cases. HR and LBO configurations demonstrated that experienced E2E latency measurements are suitable for most CAM applications.

4.7. XBI_7 Insufficient accuracy of GPS positioning

Positioning accuracy is important for automated vehicles to function properly. In the context of a cross border situation, but also degradation of operational design domain of the L4-L5 automated vehicle in case of sensor failure, positioning by GNSS might not always be available (due to blocking overhead or sensor failure) and therefore other means of positioning were researched and implemented. NL TS has executed position accuracy tests on the Remote Driving application level as well as designed and implemented a 5G positioning solution based on mm-wave 5G SA network configuration (Table 46).

Table 46: Summary of UCC/US where XBI_7 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_20: Compressed sensing positioning	NL	Remote Driving	5G Positioning	NL-3.1, 3.2, 3.5

4.7.1. CS_20: Compressed sensing positioning

NL TS

This solution focuses on augmenting positioning accuracy by taking advantage of the properties of 5G mmWave signals, which provide large bandwidth combined with multiple antenna-technology at both network and UE sides. Using compressed sensing techniques on the OFDM signal, improvement on positioning accuracy beyond the accuracy available from GNSS-type positioning even when only few reference stations are available is expected. Taking advantage of information for angle of arrival/departure available from the multi-antenna systems and the sparsity of mmWave channels, highly accurate relative positions between base station and UE can be derived by UE-based positioning.

For this purpose, several tests have been executed for generating baseline position accuracy measurement with manual driving and with remote driving, using a 4G as well as the KPN 5G SA network, and using the TU/e-AIIM and Siemens vehicles and remote driving stations in test cases NL-3.1 and NL3.2. For this purpose, a slalom test was setup, to measure the position accuracy of the remote driving application in the longitudinal direction in both networks. Figure 46 (left) shows some results of the positioning accuracy measurements of the longitudinal distance to cones in the slalom course. Figure 46 (right) shows the E2E latency of the video stream from the vehicle to the remote station. The average latency is reduced from 25 msec with 4G to 13 msec with 5G-SA.

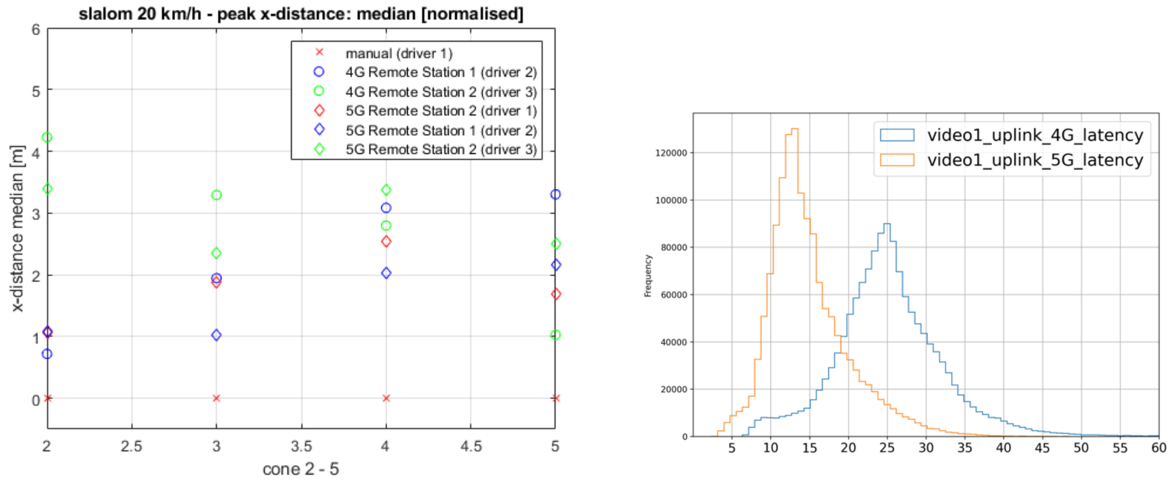
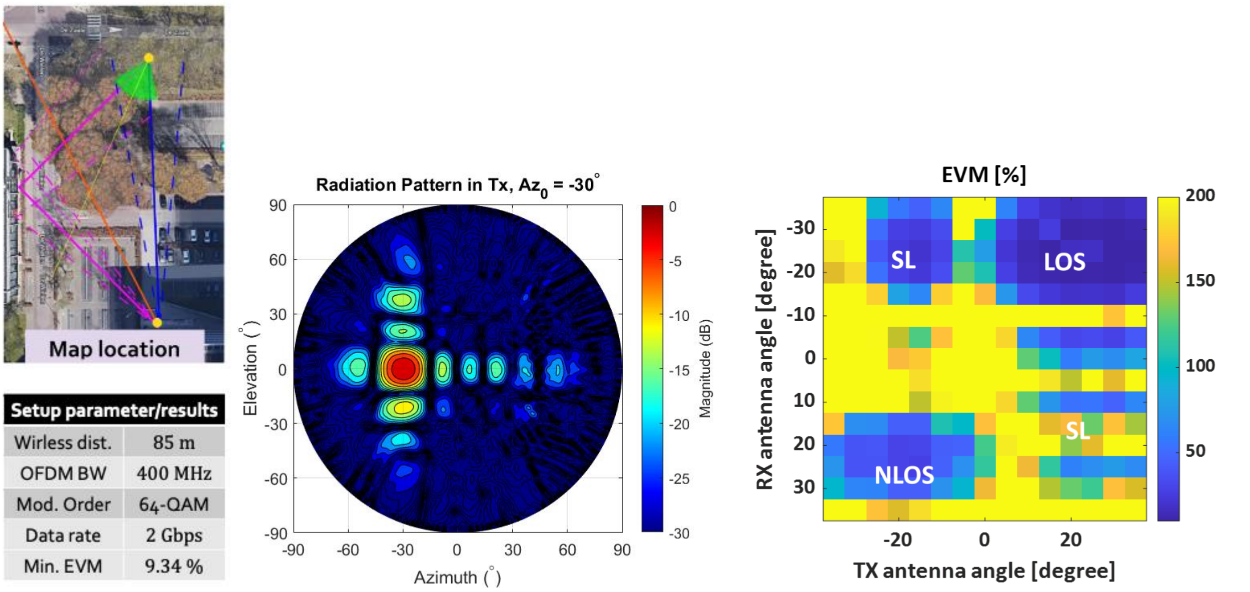


Figure 46: NL TS, Remote Driving use case with vehicle position accuracy (left) in manual driving and remote driving using a 4G and 5G-SA network, and video stream E2E latency (right).

The results from Figure 46 (left) clearly show a position delay of >1 [m] in longitudinal direction. However, no clear difference between the 4G and 5G-SA setup can be found. Further details of this analysis are published in [7]. Separately the mm-wave network was built at TU/e for testing the localisation algorithms. Measurements for the mm-wave network were performed with a simplified deployment with reduced protocol stack and experimental mm-wave RF and baseband hardware. Figure 47-left shows the deployment and its location on the TUE campus, including the antenna locations, beam sizes and field of view with beam steering, and the measurement equipment. The radiation pattern of the individual antennas is shown (Figure 47-middle), alongside a map of the resulting EVM (Figure 47-right) depending on the scan angle of both Tx and Rx antennas, allowing clear identification of LOS and NLOS components as well as spatial components due to incompletely suppressed sidelobes. The achieved EVM and throughput match expectations and the given spatial/angular resolution matches that assumed for evaluation of the localization algorithms.



Setup parameter/results	
Wirless dist.	85 m
OFDM BW	400 MHz
Mod. Order	64-QAM
Data rate	2 Gbps
Min. EVM	9.34 %

Figure 47: NL TS, mm-wave measurements at TU/e. Left: map showing antenna directions and field of view with beamforming. Middle and right: Antenna radiation pattern and measured EVM across Tx and Rx angle.

These outcomes of the radiation patterns are used in an offline localization algorithm to estimate the position accuracy. In this case, the position accuracy for line of sight (LOS) and non-line of sight (NLOS) that can be achieved is respectively 0.293 [m] and 0.4 – 0.6 [m] RMSE (see Figure 48).

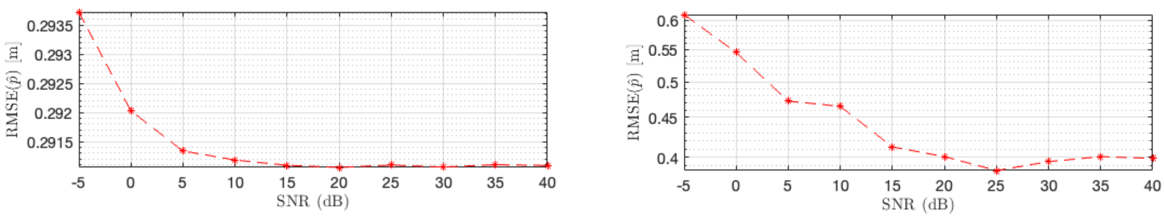


Figure 48: NL TS, RMSE of vehicle position vs. signal to noise ratio at 60 [m] from nearest base station; (left) position accuracy over LOS, (right) position accuracy over NLOS.

4.7.2. Conclusions

Compressed sensing techniques on mmWave can provide sufficient positioning accuracy. mmWave RF and baseband measurements show the importance of NLOS and LOS components in such application. In offline localization, it is shown to be able to estimate vehicle position accuracy up to 0.293 meter in case of LOS. It should be considered that this setup has a low TRL level and that, further integration and improvements are likely, requiring further research and applicability in automotive applications.

4.8. XBI_8 Dynamic QoS continuity

Along the vehicle move, geographic (physical barriers and distance to the base station) and concurrency (users of available connectivity assets) aspects have a direct influence on the QoS provided by the network. While session-based applications and services need a steady QoS, it is not stable along time and position. Specifically, in a cross-border situation the distance to the base station and the level of concurrency to the home PLMN network and the visiting PLMN network can be completely different, producing significant changes in the provided QoS. This means that the service or application needs to dynamically adapt to the QoS provided by the network what is changing in a drastic manner during the roaming stage.

The bitrate from the flows analysed to obtain the results regarding XBI_8 play an important role and, therefore, primarily throughput results are included in this section but also results related to reliability.

Table 47 show the tests cases where DE TS trialled this XBI where the adaptive video rate feature is active or not.

Table 47: Summary of UCC/US where XBI_8 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_21: Adaptive Video Streaming	DE	Extended Sensors	EDM	DE-2.1, DE-2.2

4.8.1. CS_21: Adaptive Video Streaming

DE TS

In these test cases, a video stream which is sent from one vehicle to other via 5G Uu interface is evaluated. The two vehicles are connected via WebRTC clients, managed by a server deployed in the MEC. Once the connection is set, the video stream is sent directly between the two vehicles, without passing through the WebRTC server. The video stream frames are monitored providing reliability and data rate measurements, which are described below.

Figure 49 and Figure 50 show measurements for data rate and reliability for the two specific test cases scenarios (with adaptive video rate feature active or disabled) performed in the Extended Sensors US from the DE TS. For each test case scenario, ten runs have been performed. Each of them is presented in the graphics as one of the boxes. The difference between both test cases scenarios is that in one of them, video is transmitted at a constant data rate of 10 Mbps and 30fps, and in the other, data rate varies depending on the current network performance, adapting the video bitrate. In the reliability figures, it is worth to remark that for the adaptive bitrate video test case the mean value is around five percent better than for the constant bitrate video test case. When video is transmitted at a constant rate and network performance degrades, a high number of video frames are lost or discarded due to high latency. This can be improved thanks to the adaptive video feature introduced by the DE TS (CS_21).

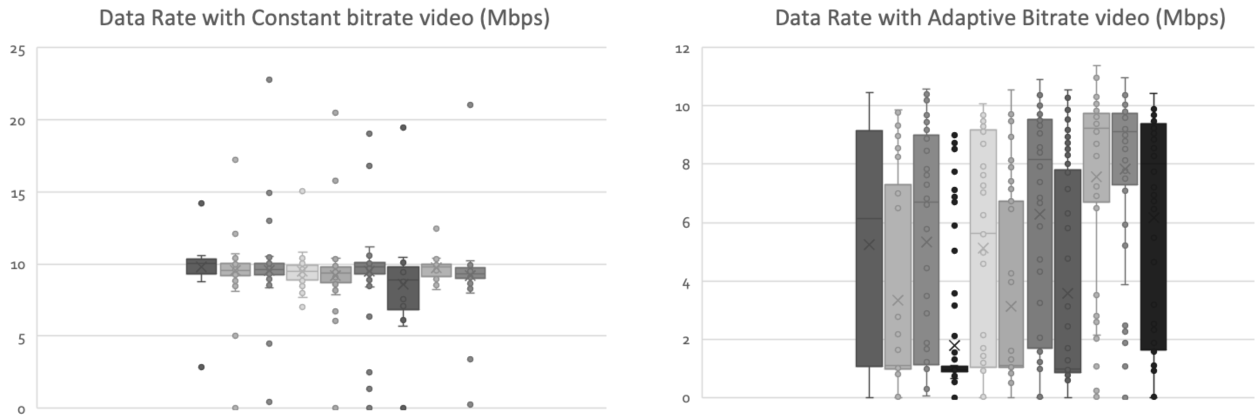


Figure 49: DE TS, constant-video (left) and adaptive video (right) test cases - user experienced data rate (Mbps)

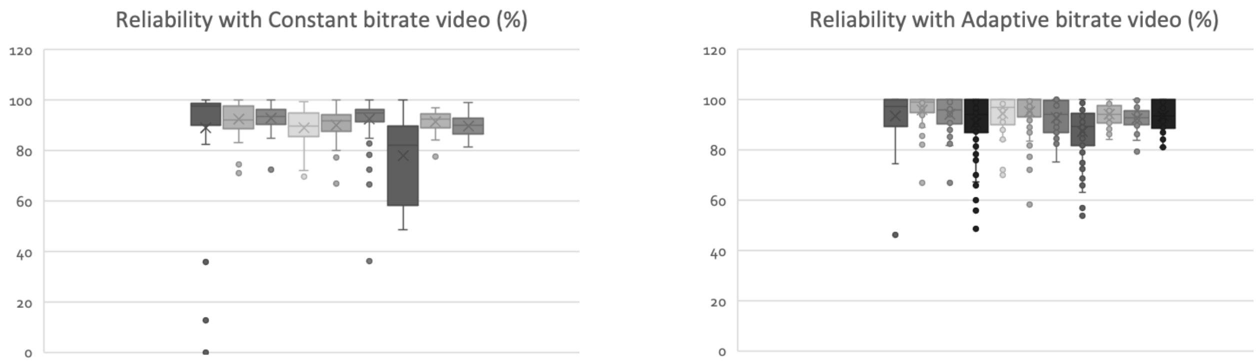


Figure 50: DE TS, constant-video (left) and adaptive video (right) test cases – reliability (%)

DE TS contribution to ES-PT CBC

In the framework of Vehicle QoS Support US, ES-PT has streamed video from the ALSA bus to a server hosted in the 5G-MOBIX network. This test consists of a real time video stream with HD resolution encoded on a 3 Mbps stream for the on-demand video content providing industry standard codec parameters. This was performed using an on-board server with an ethernet connection to a 5G MiFi device, with no external antennas, which has been verified in a wired network providing the internet to be valid for the intended use and traffic demand.

The results of this test case show low values for reliability (Figure 51) that are directly translated into poor quality of video (pixelated and blurry) and interruptions, which are more significant during the handover process. This is mainly because of the connectivity limitations of the MiFi.

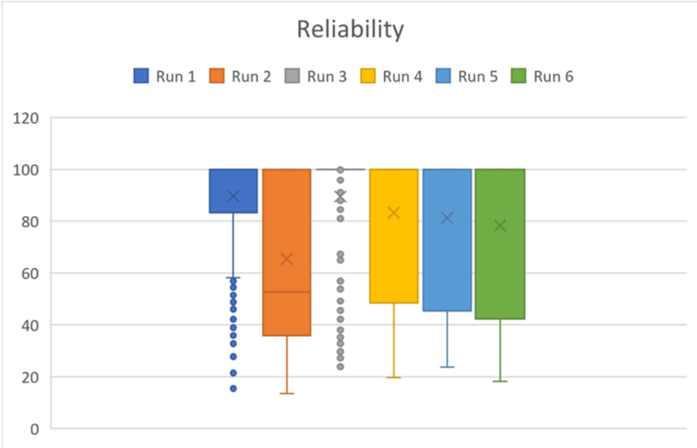


Figure 51: DE TS to ES-PT CBC, reliability obtained by ES-PT with constant bitrate (%)

DE contribution in ES-PT CBC has showed how the adaptive video rate is suitable to manage these situations when the connectivity is not enough to handle the required data rates. The tests done in DE (Berlin) were repeated in the ES-PT CBC and even better results were obtained in terms of reliability improvement.

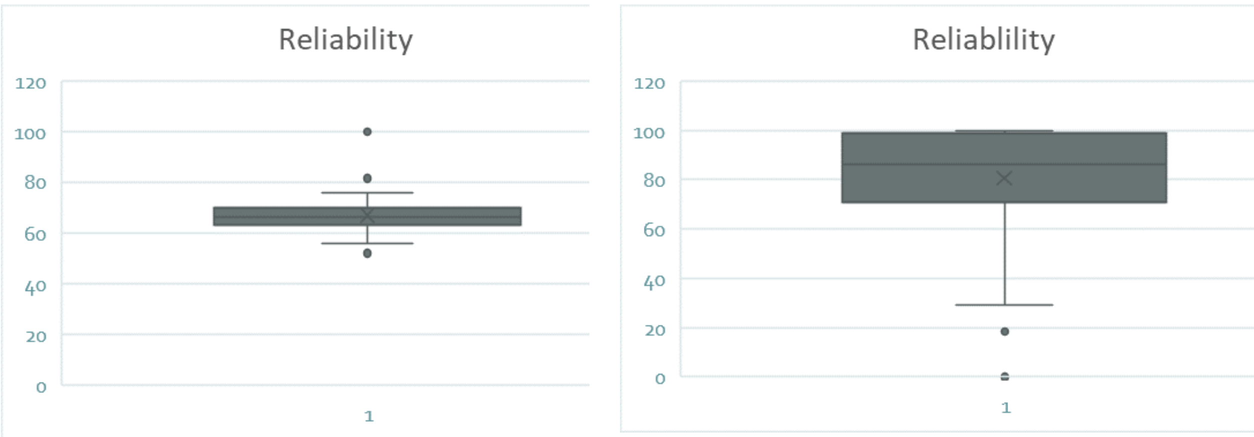


Figure 52: DE TS to ES-PT CBC, reliability with constant (left) and adaptive (right) bitrate (%)

In the tests done by DE in the ES-PT CBC (Figure 52), the median reliability of video streaming using constant bitrate was 67.03% while the median reliability using adaptive bitrate was 87.58%. This means that the reliability increased around 20% when using the adaptive bitrate solution of the DE TS.

4.8.2. Conclusions

The results of the adaptive video solution proposed by DE TS have shown that thanks to the reduction of the data rate in conditions where the network quality is degraded, the reliability is improved. This is because, less traffic under worse conditions, results in lower packet loss i.e., the connection presents a bottleneck and CS_21 allows the adaptation of the traffic flow to it. This is especially significant in the ES-PT CBC, where the reliability improved around 20% when using the adaptive bitrate solution. The reliability improvement was higher in the ES-PT CBC than in Berlin because the network performance in terms of data rate was lower in the ES-PT CBC. The higher reliability enforces the QoS with lower packet loss, less visual artifacts and fewer frames drops. If the network allows the UE to achieve the target bitrate (10 MBits/s in the tests), then the adaptive bitrate functionality does not need to act and its effect is lower.

4.9. XBI_9: Geo-constrained information dissemination

The investigation of this XBI aims at shedding light on the effectiveness of 5G in geo-constrained information dissemination, in the context of cross-border environments, as opposed to V2V mechanisms (CS_24) that do not rely on infrastructure. The most important results that need to be provided for the analysis of XBI_9 is related to latency and reliability. The target is to assess the level of service disruption when traversing the borders and rely on the coordination of network and application components between the two PLMNs.

An important aspect, in the context of the 5G enabled solution (CS_23), is related to the inter-MEC message exchange, where added latency in messages received -from another area other than the current UE area, may have a big impact in case of critical timing requirements for certain application, as it is in the platooning case. Also, the latency that is added by sending the infrastructure messages from the RSUs to the MEC can be very important and, therefore results for an agnostic test are helpful.

Table 48 summarizes the CBC/TS and UCC that trialled XBI_9.

Table 48: Summary of UCC/US where XBI_9 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_23: Uu geobroadcast	ES-PT	Advanced Driving	Lane Merge	ES-PT-1.1, ES-PT-1.2 and ES-PT-1.4
			Overtaking	ES-PT-2.1 to ES-PT2.6
			Cooperative Automated	ES-PT-5.6 and ES-PT-5.7
	DE	EDM	Surround view	DE-2.1, DE-2.2
		Platooning	AsseRSU	DE-1.2, DE-1.3
	NL	Advanced Driving	Cooperative Collision Avoidance	NL-2.1,2.2, 2.3, 2.11, 2.12, 2.21, 2.41, 2.42, 2.43
		Extended Sensors	CPM	
CS_24: PC5 geobroadcast	DE	Platooning	AsseRSU	DE-1.1

4.9.1. CS_23: Uu geobroadcast

ES-PT CBC

Geobroadcast is implemented by using an MQTT topic structure consisting of a quadtree path based on spherical Mercator projection. Each topic refers to a specific message dissemination area, named a tile, that can be calculated using the latitude and longitude values. A station publishes messages to its own tiles while subscribes to its tile and the 8 adjacent ones. Following this topic structure to publish and subscribe ensures that messages are only disseminated in the relevant areas. Figure 53 shows a test case where a connected vehicle with a 5G OBU (station ID 3306), represented by the blue pin on the map, performs a lane merging manoeuvre. The OBU starts the run parked at the ES side of the border (tile ⓪ in Figure 53-left). The 5G connected RSU (station ID 3308), with the red map pin, is publishing CPM messages in its own tile (tile ⑩), which is not any of the OBU's adjacent tiles, therefore the OBU does not receive CPM messages published by the RSU. As the OBU crosses the bridge towards PT, it moves through tiles ② to ⑧ without receiving any CPMs. When it reaches tile ⑨ (Figure 53-right), that is adjacent of the RSU's tile, it starts receiving the CPMs.

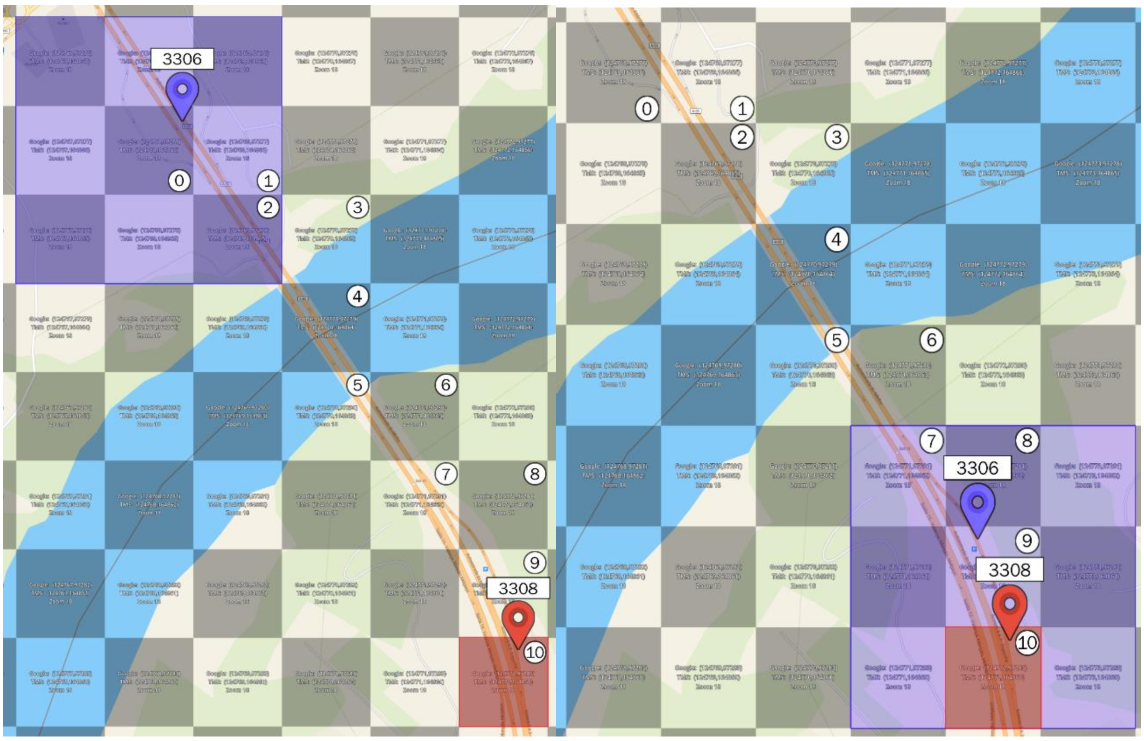


Figure 53: ES-PT CBC, Uu geobroadcast test case. Left: 5G OBU's initial position. Right 5G OBU's final position.

Figure 54 reflects the movement of the OBU between the tiles and marks the tile changing points and a HR handover that happened in the beginning of the run. It also shows the CPMs' uplink latency (from the RSU to the MEC MQTT broker) and the downlink latency (from the broker to the OBU) stacked on top of the uplink values. It can be seen that chart only includes downlink values when the OBU enters tile ⑨, while it the uplink values are present throughout the entire test.

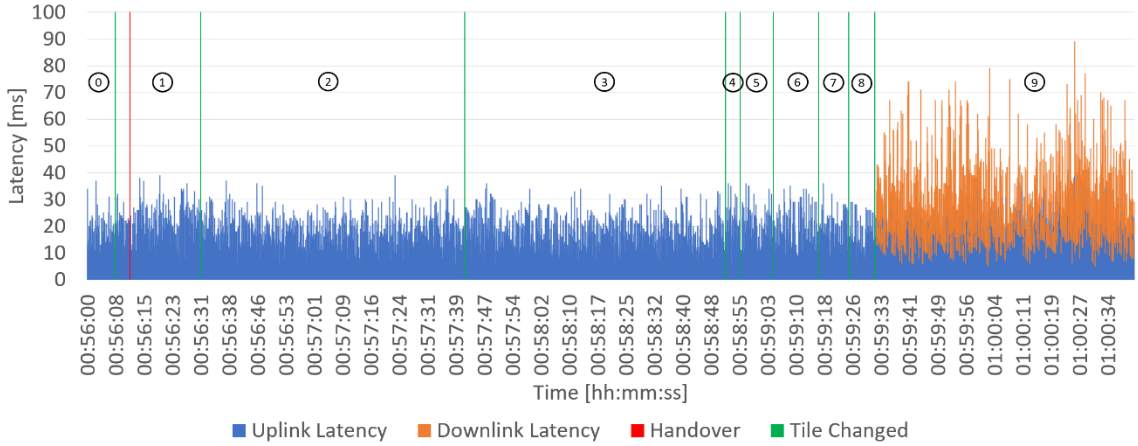


Figure 54: ES-PT CBC, Uu geobroadcast mechanism with mobility (5G OBU subscribing to CPM messages from 5G RSU via MEC MQTT broker).

Values of the uplink, downlink and E2E latencies are shown in Table 49, Table 50 and Table 51 respectively and Figure 55 is the distribution chart of the mentioned values. It was found that the proposed geobroadcast approach is able of handling the required message delivery pattern in cross border corridors scenarios achieving 100% reliability since all the 693 CPMs published by the RSU (during the time the OBU was inside tile ⑨) were successfully received by the OBU.

Table 49: ES-PT CBC, Uu geobroadcast, 5G RSU – MEC MQTT broker (uplink) latency (ms).

# total samples	Mean	Median	Std. Deviation
3593	18	17	6,27
Max	**Min**	**CI 95%**	**Percentile 95**
5	39	0,205147	29

Table 50: ES-PT CBC, Uu geobroadcast, MEC MQTT broker – 5G OBU (downlink) latency (ms).

# total samples	Mean	Median	Std. Deviation
693	17,34	15	11,33
Max	**Min**	**CI 95%**	**Percentile 95**
5	64	0,843572	45

Table 51: ES-PT CBC, Uu geobroadcast, 5G RSU – MEC MQTT broker – 5G OBU (E2E) latency (ms).

# total samples	Mean	Median	Std. Deviation
693	35	33	12,71
Max	**Min**	**CI 95%**	**Percentile 95**
13	89	0,946629	61,4

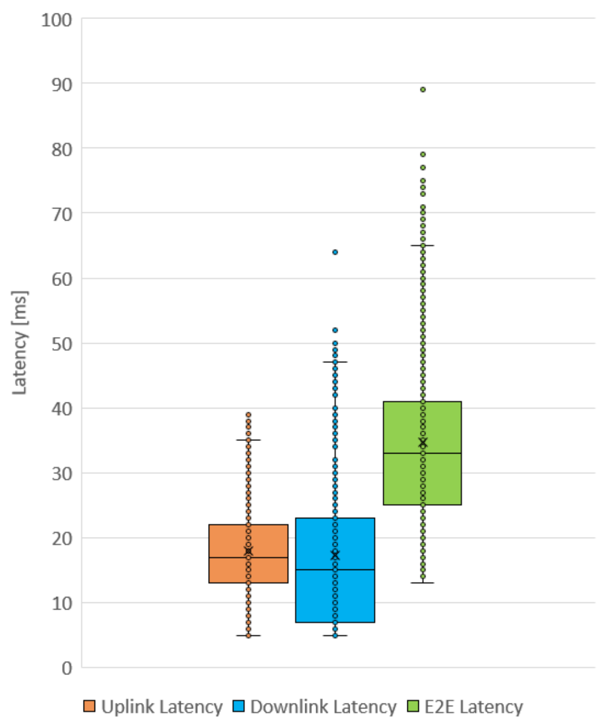


Figure 55: ES-PT CBC, Uu geobroadcast, 5G RSU – MEC MQTT broker – 5G OBU, uplink latency (ms) – downlink latency (ms) – E2E latency (ms)

DE TS

The assessment of CS_23 was based on test cases for the Platooning and EDM UCC/US.

Platooning Results

Regarding the geobroadcast feature of the test cases, in the DE TS, messages sent from an eRSU different than the one allocated for the current vehicle area are only forwarded by the geobroker if the vehicle is driving in the direction of that eRSU area. If not, messages are discarded directly in the MEC, saving many network resources and improving its performance.

The measurements in the Platooning US are focused on the platooning flow (platooning control messages between two vehicles that are close by) and on the EDM flow (comprised of all messages produced by the infrastructure deployed in the DE TS with the aim of enhancing the vehicle's perception) that are sent through the Uu interface to the vehicles subjected to geo-constraints applied by the geobroker, which is deployed in the MEC. Measurements focused on E2E latency perceived, from the generation of a message till the eventual delivery to the intended vehicle.

For each test case scenario, ten runs have been performed, each of them is presented in the graphics as one of the boxes. In Table 52 and Figure 56 the overall E2E-latency results for the Uu specific test case in the Platooning US are presented for the EDM flow. In the Table 53 and Figure 57, the results from messages that are sent from the eRSU to the MEC in its domain and then directly to the vehicle are presented for the EDM flow. In Figure 57, results are presented for messages where there is an extra hop in the communication, meaning that messages are sent to the vehicles by an eRSU located in another domain, crossing first trough two different MECs in two MNOs. It is very clear that the single-MEC results are around 15 ms lower than the inter-MEC results, which is expected due to extra hop in the latter case. It is important though to highlight the relatively short increase on E2E delay, around 10%, when an additional hop is introduced, which coincides with the results measured in the inter-MEC agnostic test for RTT, presented in section 4.5.4.

Table 52: DE TS, Uu Test Case – eRSU – single-MEC broker – OBU E2E-latency (ms)

# total samples	Mean	Median	Std. Deviation
8060	131,55	92,51	141,15
Max	**Min**	**CI 95%**	**Percentile 95**
993,3	31,25	3,08149604	429,21

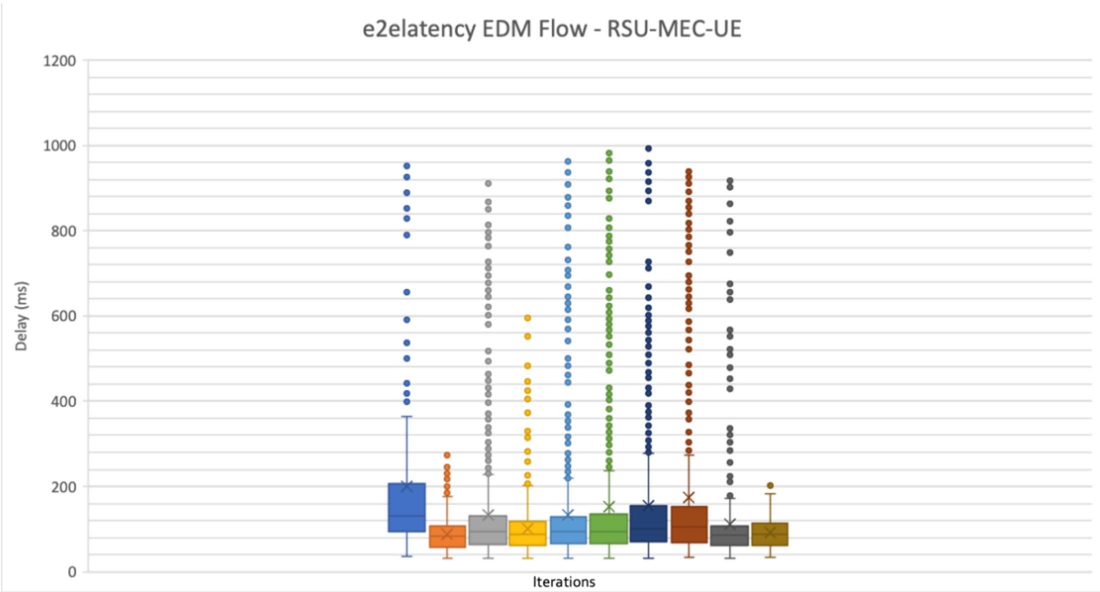


Figure 56: DE TS, Uu Test Case – eRSU – single-MEC broker – OBU E2E-latency (ms)

Table 53: DE TS, Uu Test Case – RSU – inter-MEC broker – OBU E2E-latency (ms)

# total samples	Mean	Median	Std. Deviation
10890	147,018	76,49	187,30
Max	**Min**	**CI 95%**	**Percentile 95**
996,4	21,07	3,518	620,39

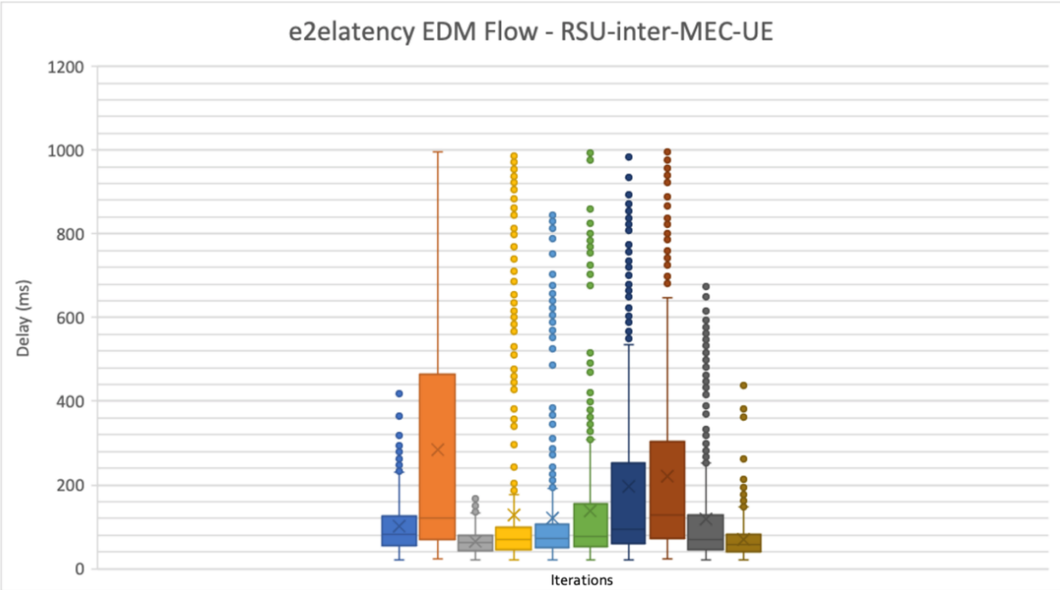


Figure 57: DE TS, Uu Test Case – RSU – inter-MEC broker – OBU E2E-latency

In Figure 58, E2E-latency for the platooning messages is presented. These messages are generated by the platooning leader vehicle and then sent to the platooning follower vehicle via the MQTT broker for the Uu test case. The latency values for this flow are lower than for the EDM flow, because in this case, both OBUs are clients connected to the same MNO network, and do not need to travel from TUB's infrastructure network to the MNO's network.

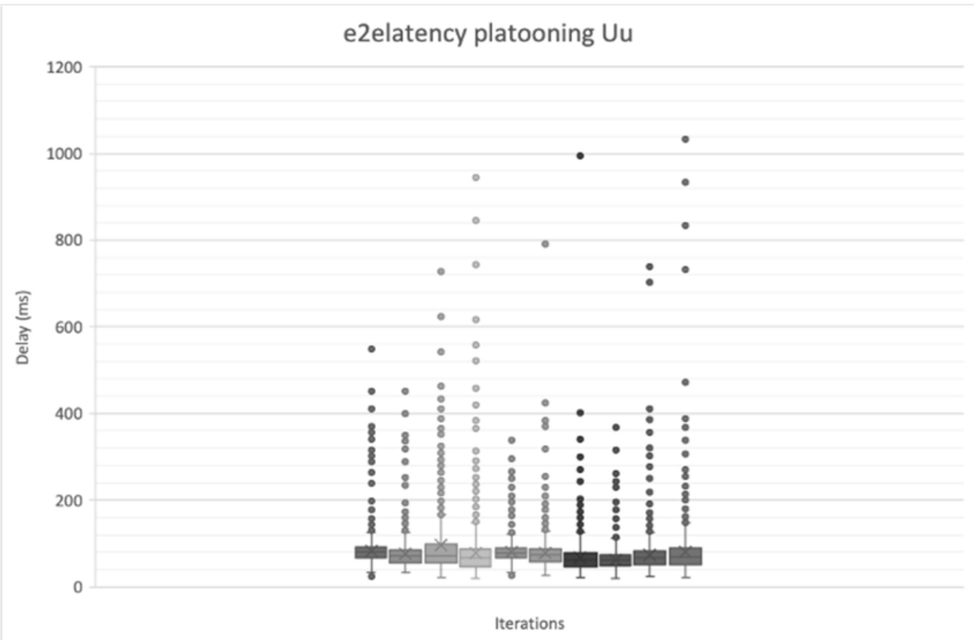


Figure 58: DE TS, Uu Test Case – OBU leader – MEC broker – OBU follower E2E-latency (ms)

Table 54: DE TS, Uu Test Case – OBU leader – MEC broker – OBU follower E2E-latency (ms)

# total samples	Mean	Median	Std. Deviation
10143	76,86	70,65	51,99
Max	**Min**	**CI 95%**	**Percentile 95**
1045,85	19,95	1,012	125,73

The packet loss for the Uu and the hybrid test cases is zero. This is ensured by the TCP protocol which ensures that lost packages are retransmitted, this is translated to hundred percent reliability. On the other hand, as can be seen in the delay graphics, there are some cases where messages have a high delay of over more than 500 ms, which means that these messages would need to be discarded and categorized as unreliable as they could be dangerous if still used in the control of the vehicle or by other functions of the application.

Regarding the Uu geobroadcast considered solution and the results obtained by the DE TS, it does not meet the requirements defined by the latency target KPI, which is 40 ms for the platooning US. This solution is thus only appropriate only for messages in applications with low sensitivity to delays and high reliability requirements.

Extended Sensors Results

Extended Sensor US implements EDM messages that are used for the vehicle discovery service. In this case, vehicles send periodical ETSI CAM messages to the EDM with information about position, speed and heading of the vehicle, that is stored in a time-series database. The EDM is used by the vehicle discovery service (VDS), also deployed in the MEC. The VDS acts as a third-party service that is trusted by surrounding vehicles in order to identify and connect to neighbour vehicles and manage signalling and negotiation. The VDS acts as a local centralised solution to allow a more efficient and coordinated communication, instead of forcing a vehicle willing to communicate to query each neighbour vehicle one by one. VDS could be a facilitating service for OEMs implementing Extended Sensors functionalities. Third-party SW suppliers could use VDS to select relevant vehicles for their application or service.

The VDS filters the vehicles stored in the EDM register considering their geoposition and orientation to respond to the queries. When a VDS receives a ETSI CAM message of a vehicle that is approaching a neighbour MEC, it forwards it to the neighbour MEC. Thus, EDMs of neighbour MECs are synchronised to smooth transitions. Figure 59 shows the architecture of the DE TS Extended Sensor US with the MEC interconnection.

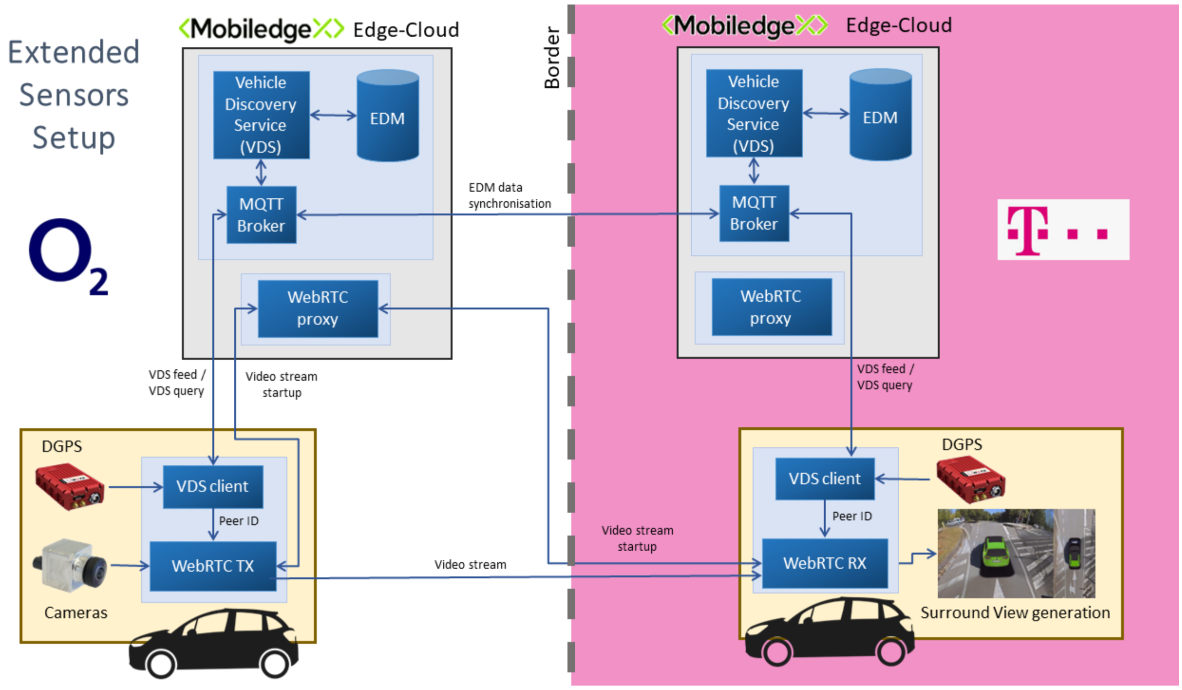


Figure 59: DE TS, Extended Sensors' MEC interconnection

The messages exchanged between the vehicles and the MEC are sent by MQTT. In the trials conducted in Berlin, the RTT of MQTT messaging was measured and the results are shown in Table 55. The CAM messages have a period of 100 ms, so a RTT of 45 ms is low enough to enable their processing. However, the standard deviation is quite high (13 ms), and some outlier values are above 100 ms. This fluctuation depends on several factors like the network capacity or shadowing and reflection effects. In certain services this may render the operation problematic i.e., occasionally not working. The RTT or latency results are lower than in the Platooning US due to the different setup used (as commented above) and the lighter messaging: the Platooning US requires sending information about the objects detected by the infrastructure while in Extended Sensors only the ego-vehicle information is sent.

Table 55: DE TS, Adaptive Test Case – OBU – MEC broker – OBU RTT-latency (ms)

# total samples	Mean	Median	Std. Deviation
1096	48	45	13
Max	**Min**	**CI 95%**	**Percentile 95**
343	32	2.58E-02	64

DE TS Contribution to ES-PT CBC

One of the planned contributions of the DE TS to the ES-PT CBC was the comparison between the far-edge or Edge-Cloud used in Berlin (MobiledgeX) and the MEC used in the ES-PT CBC. For this comparison, the

VDS and EDM instances described in the previous section were deployed in the ES-PT CBC MECs. The complete DE Extended Sensors US was trialled in the ES-PT CBC and the RTT of the MQTT messaging between the vehicle and the NOS MEC was measured. The results are shown in Table 56.

Table 56: DE TS to ES-PT CBC, OBU – MEC broker – OBU RTT-latency (ms)

# total samples	Mean	Median	Std. Deviation
1848	39	29	49
Max	**Min**	**CI 95%**	**Percentile 95**
1290	13	7.14E-02	91

It can be noted that the RTT obtained using the NOS MEC is significantly lower than the RTT obtained in Berlin with MobiledgeX. This an expected result, as a far-edge or edge-cloud is expected to perform worse in terms of latency or RTT than a MEC. However, an edge-cloud like MobiledgeX has some advantages. For instance, it is publicly accessible from the internet, so it is easier for remote testing. On the other hand, the ES-PT MECs need to be physically under the coverage of the corresponding ES-PT network using the specific SIM (either NOS or TELEFÓNICA), to access the MEC. So, tests with UEs are limited to very concrete geographical areas. In addition, MobiledgeX offers a web interface to monitor the status of instances and run new nodes, similar to a Cloud infrastructure., that facilitates the deployment and debugging for CAM developers.

To sum-up, if the lowest possible latency is intended, then a canonical or ETSI MEC is clearly a better choice. If the latency requirements of the CAM application are more relaxed and are met by an edge-cloud or far-edge solution, then this option can reduce time-to-market, facilitating deployment and debugging.

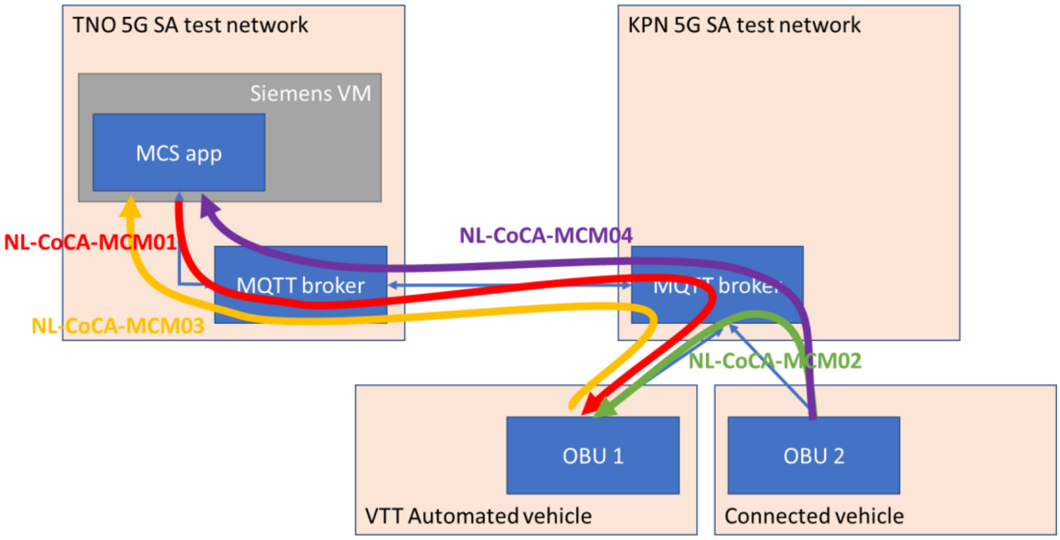
NL TS

The NL TS has two 5G SA test networks from KPN and TNO, both using MEC routing via an MQTT server on the MEC. Both MQTT servers route CAM traffic using topic exchanges, and the geo-constrained message exchange is implemented using quadtrees as topics. This allows a UE to subscribe to messages within a tile of relevance, and to avoid an overload of information from irrelevant tiles. This architecture is similar to that in the ES-PT TS and allowed the cross-border testing of the Collision Avoidance US from the NL TS at the ES-PT TS in section 4.6.1.

For this solution, it is the responsibility of the UE to publish messages with the correct location tile in the topic, and to update its subscription to the upcoming tiles en-route in a timely manner to avoid missing any information. It is the responsibility of the MNOs to exchange the relevant information across borders, for example using an inter-MEC exchange as presented in section 4.5.4.

The main benefit of geo-constraining the information exchange is to reduce the data rate for CAM applications, by avoiding the exchange of geographically irrelevant information to a UE. In the Extended Sensors US for example, a test vehicle only subscribes to CPM messages in a small tile around its own location to limit the downlink data rate to some 16 kbps. By comparison, the roadside camera systems exchange all detected vehicles passing the motorway in CPM messages of 100 m or 1 km sections. This could result in a downlink data rate of 1.6 Mbps, which may be useful for some applications, but not for the lane change manoeuvre in this US. Geo-constraining the traffic by topic filtering on the MQTT server at the MEC is applied in all test cases of the TNO and KPN 5G SA test networks. The average E2E latency (TE-KPI1.3) between the test vehicles is between 20 and 25 msec (see Table 32 in section 4.5.4 and section 4.11.1), while message delivery ratio (TE-KPI1.6) remains close to 100%.

The Collision Avoidance US uses three data flows of MCM messages as shown in Figure 60. The application is tested in an I2V and a V2V scenario. In the I2V scenario, a road side MCS application on the MEC receives MCM messages from test vehicles (NL-CoCa-MCM03 and 04), and sends collision avoidance instructions to the test vehicle in MCM01. The average data rate for the uplink between test vehicle OBU1 and the MCS application is in the order of 37 kbps, and the downlink is 47 kbps. In the V2v scenario in test case (NL-2.3), OBU2 sends its MCM messages to OBU1, without communication with the MCS application. The V2V data rate from OBU2 is in the order of 21 kbps.



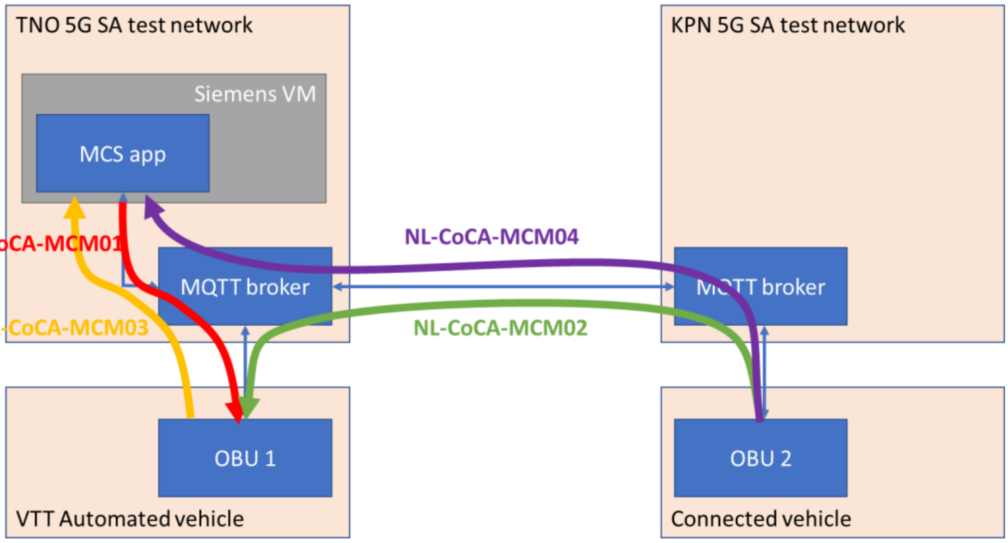


Figure 60: NL TS, Collision Avoidance communication network setup and data flows, with test vehicles connected to a single network (top) and to different networks in a border crossing scenario (bottom).

The following results report on the V2V communication NL-CoCa-MCM02 between OBU2 and OBU1 in a single network scenario (Figure 60-top) and in a border crossing scenario (Figure 60-bottom). There is no hand-over in the cross-border scenarios (test case NL2-1 to 2-3) and both test vehicles remain connected to their different home networks throughout the test run, while the MCM traffic has to be exchanged between the MQTT brokers.

The impact on the communication performance is shown in the following tables. The MQTT geographic topic filtering and data exchange between the MECs does not affect the reliability. The message delivery ratio remains high enough to meet the application requirements (Table 57). The E2E latency in the single network scenario is similar to that for the Extended Sensors US reported above (Table 58). In the cross-border scenario an extra delay of some 6 – 7 msec is introduced when traffic has to be exchanged between the networks.

Table 57: TE-KPI1.6 – NL TS, Message Delivery Ratio in % for geo-constrained messages exchange in cross-border scenarios for the Collision Avoidance US in the NL TS

Border Crossing	Network(s)		avg	median	stdv	max	min	CI 95	Perc.95
No	KPN (Figure 60-top)	5G SA	99.9	100	0.20	100	99.5	99.7-100	100
Yes	KPN+TNO without handover (Figure 60-bottom)	5G SA	99.9	100	0.17	100	99.6	99.7-100	100%

Table 58: NL TS, TE-KPI1.3 – E2E latencies in msec for geo-constrained messages exchange for the Collision Avoidance US in the NL TS

Border Crossing	Network(s)		avg	median	stdv	max	min	CI 95	Perc.95
No	KPN (Figure 60-top)	5G SA	27	26	8	109	13	26.3-27.0	40
Yes	KPN+TNO without handover (Figure 60-bottom)	5G SA	34	32	8.5	154	13	33.0-34.1	48

4.9.2. CS_24: PC5 geobroadcast

DE TS

In this section, the results achieved in the Platooning US when using the PC5 interface for geobroadcasting are presented. Again, there are two different flows as for the Uu case, the EDM (I2V - RSU -> OBU) and the platoon flows (V2V - OBU -> OBU).

In Figure 61, packet loss and latency results for the EDM flow tested in the PC5 test case are presented as a function of the distance between the vehicle and the eRSU. For latency, distance does not seem to have any impact, meaning that if the vehicle and the eRSU antennas have good line-of-sight conditions, the latency is not affected. As for reliability, the graphic shows that it degrades when distance increases, since for some time windows, packet loss increases substantially. Also, it is highly dependent on the line-of-sight conditions between OBU and eRSU.

In the DE TS, observations have shown differences in the PC5 interface coverage range between winter and summer, with a high impact of trees leaves that grew during the spring and made direct line-of-sight conditions worse compared to winter.

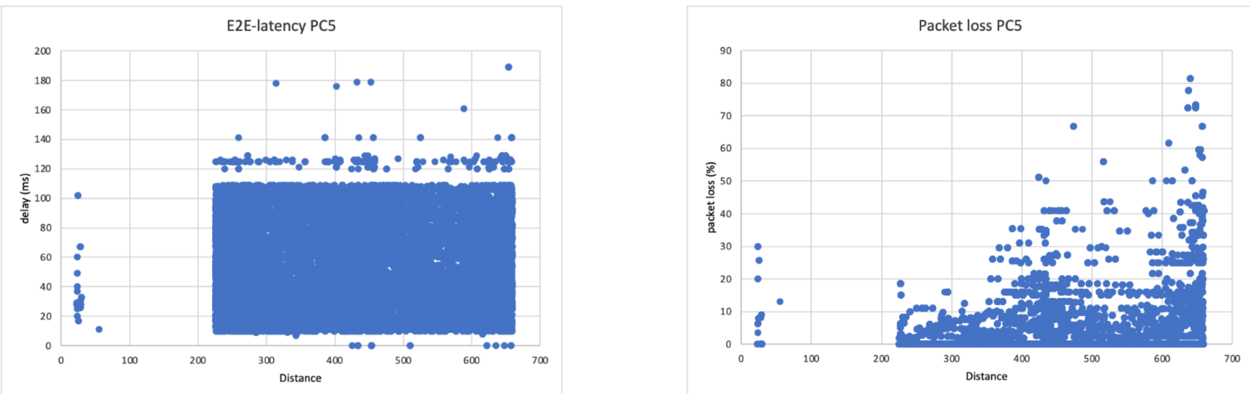


Figure 61: DE TS, PC5 test case – RSU – OBU latency vs distance (left) and packet loss vs distance (right)

Figure 62 show E2E-latency and packet loss for the platooning flow when messages are transmitted directly between the two vehicles via the PC5 interface. In this case, both vehicles are usually close by and radio conditions are very good. Compared to the eRSU – OBU results, where conditions change with the vehicle's position, latency values are below the target KPI defined for platooning E2E-latency. For the same reason, with good radio conditions, reliability is close to hundred percent, as the graphic shows almost no packet loss in these tests.

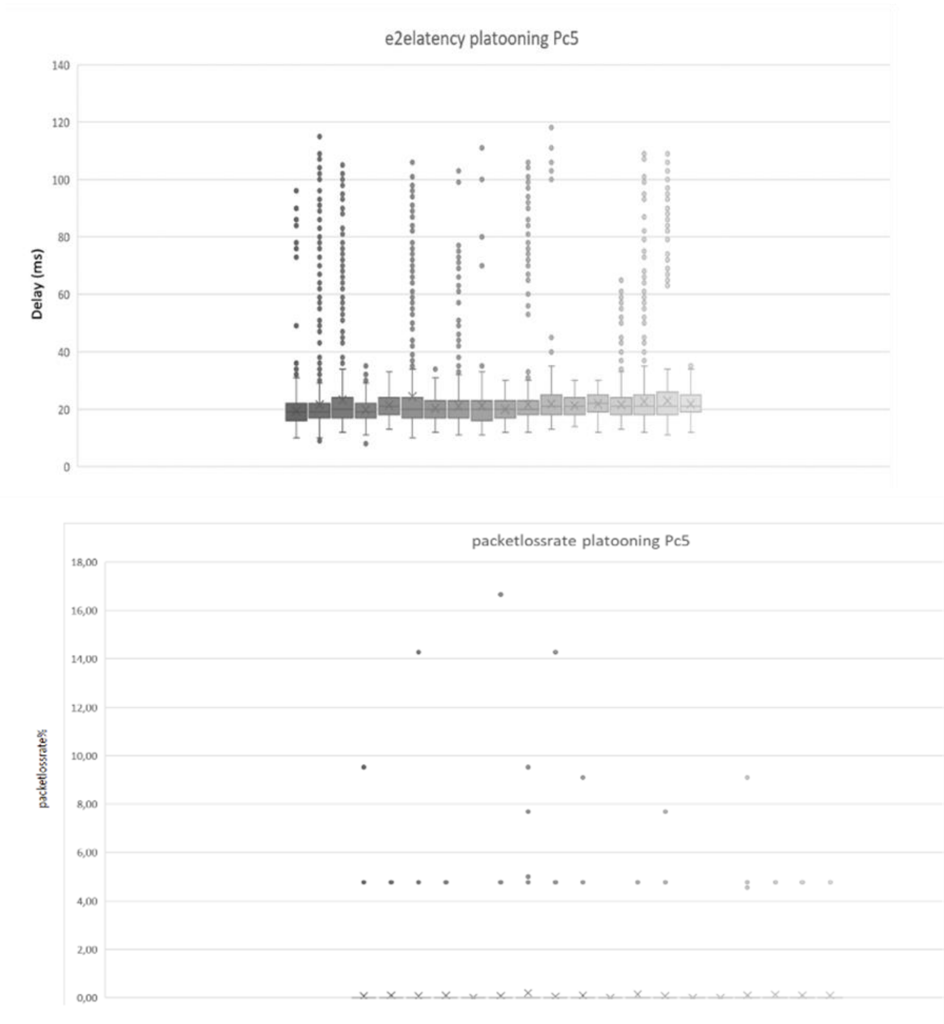


Figure 62: DE TS, PC5 Test Case – OBU – OBU E2E- latency (top) and packet loss (bottom)

Thanks to the transmission properties from PC5, messages, which are broadcasted, are only received by the units that are in near locations. This feature can be used to define different coverage areas for each eRSU. In the DE TS, latency is in general lower than for the Uu geobroadcast solution, but on the other hand, reliability is highly dependent on the dynamics of the situation.

4.9.3. Conclusions

The main advantage of geo-broadcasting is that the bandwidth and data rate used for dissemination of messages are drastically reduced, which saves network resources and avoids overloading the UEs.

PC5 communication gets lower latencies than Uu geobroadcast but it depends on the distance between the sender UE and the receiver UE and the obstacles on the road between them, that can cause interferences that decrease the reliability.

4.10. XBI_10: mmWave applicability

Specific bands in the mmWave spectrum (24GHz – 100 GHz) has been allocated for 5G networks. Particularly, in Europe, band between 24,25 and 27.5 GHz is allowed for deployment of 5G mmWave with benefits expected like higher capacity for data delivery and spectrum that can be dedicated to vertical actors. Although this study is not directly linked to a cross-border environment, it has been assessed since it presents an interest in CAM domain. Hence, the main metrics evaluated are network KPIs obtained during US trials (Table 59) with this technology: total throughput, E2E latency, packet loss rate and application data rate.

Table 59: Summary of UCC/US where XBI_10 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_25 mmWave 5G	FR	Agnostic	NA	TCA-FR-02
		Advanced Driving	Assisted Infrastructure	FR-1.2 and FR-1.4
	KR	Remote Driving	mmWave	KR2.1, KR2.2 and KR2.3
		Vehicle QoS Support	Tethering	KR1.1, KR1.2 and KR1.3

4.10.1. CS_25: mmWave 5G

KR TS

KR TS tests two use cases, Remote Control and Tethering via Vehicle, to validate 5G mmWave applicability.

For the validation of the Remote Driving UCC, a field trial was conducted on May 3, 2022, at the autonomous vehicle proving ground located at KATECH premises in Cheonan-Si, South Korea. During the field trial, received SNR (KR1.2), uplink data rate (KR1.2), and RTT (KR1.3) were measured.

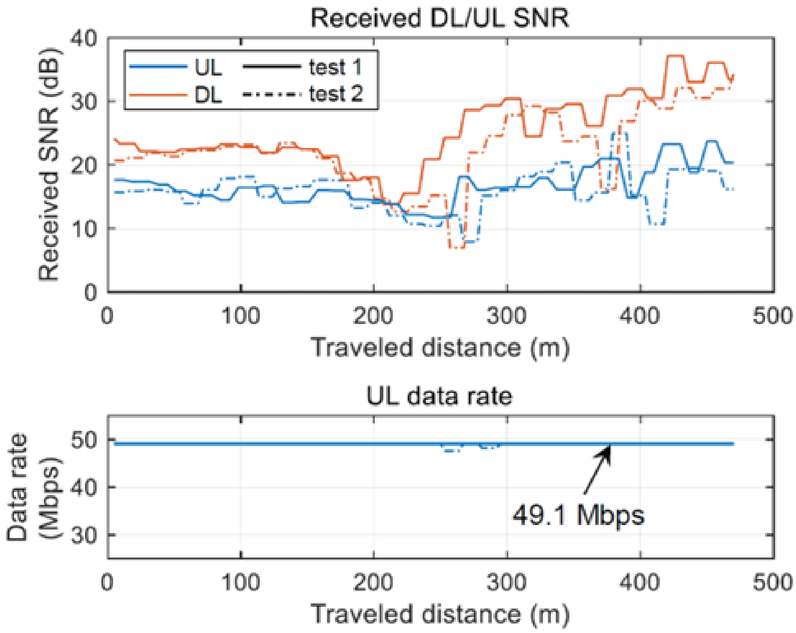


Figure 63: KR TS, received SNR and uplink data rate vs. traveled distance

Figure 63 plots the received downlink and uplink SNRs according to the travelled distance. From the figure, it can be observed that the received uplink SNR is changed by the uplink TPC performed by the vehicle UE based on the measured downlink SNR. The figure also shows the uplink data rate versus the travelled distance. It can be seen from the figure that the system yields an uplink data rate of 49.1 Mbps except for when the link suffers from slight channel fading during the second test. Nevertheless, there was no packet loss observed in the higher layer owing to the HARQ operation.

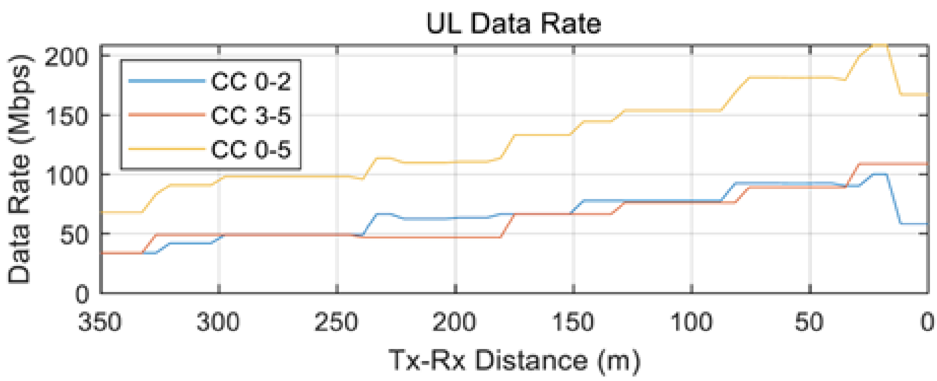


Figure 64: KR TS, Uplink data rate vs. Tx-Rx distance

To evaluate the peak uplink data rate of the system, we have conducted an additional measurement. Figure 64 shows the physical-layer uplink data rate according to the distance between gNB (Rx) and vehicle UE (Tx). It can be seen from the figure that the peak uplink data rate of 209 Mbps was achievable when the vehicle UE configured with six CCs (component carriers) is close enough to the gNB, where each CC has 100 MHz bandwidth.

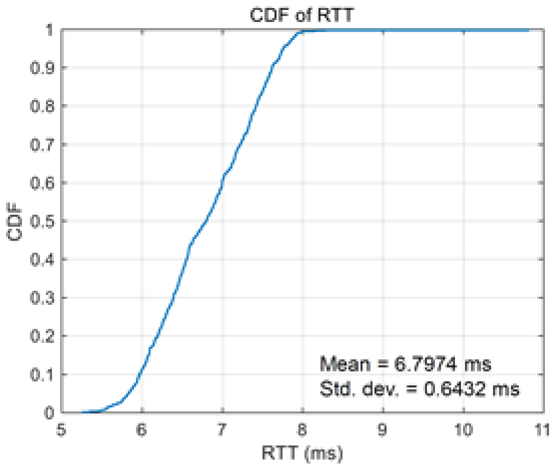


Figure 65: KR TS, CDF of RTT

Figure 65 shows the Cumulative Distribution Function (CDF) of RTT. During the field trial, an average RTT of around 6.8 ms can be achieved, which is sufficiently acceptable performance considering that in 3GPP, E2E latency of 5 ms, which is a one-way latency, is defined as a target KPI of Remote Driving. Moreover, the standard deviation of RTT is measured to be 0.6432 ms, which is very small compared with the mean value. This indicates that a variation in latency that occurs due to the mobility of the vehicle is very small.

For the validation of the Tethering via Vehicle use case, a field trial was performed on Nov. 26, 2020, on a highway test track on Highway 45 of Korea (Yeoju JCT-Gamgok IC), and measurement data were obtained in terms of user-experienced data rate (KR-2.1), reliability (KR-2.2), and mobility interruption time (KR-2.3).

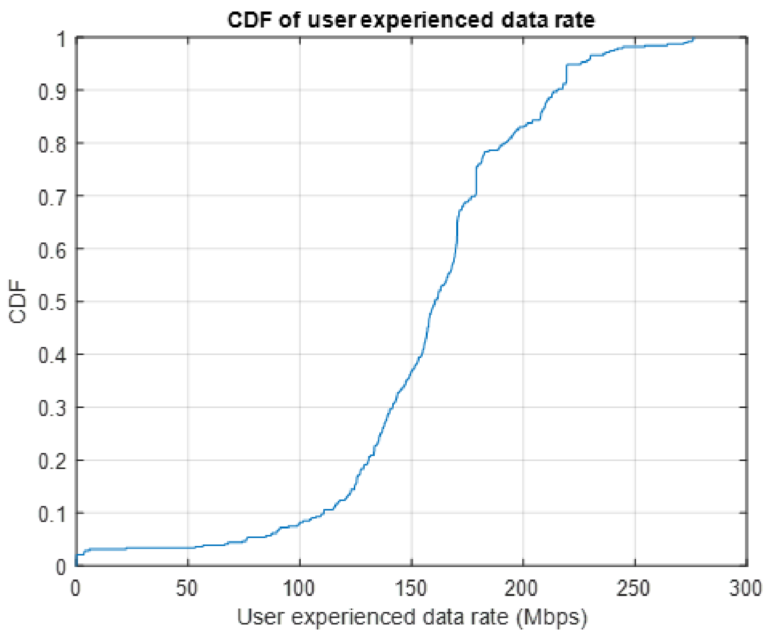


Figure 66: KR TS, CDF of user experienced data rate

As shown in Figure 66, the CDF of the user-experienced data rate was measured at the physical layer of the vehicle UE. Employing an adaptive modulation and coding (AMC) scheme along with the channel quality information (CQI) feedback, a set of modulation order (from QPSK to 64QAM) and code rate (from 0.245 to 0.889) is adaptively selected. It can be observed that at least 115 Mbps of user-experienced data rate is achievable for 90% of the time during the test.

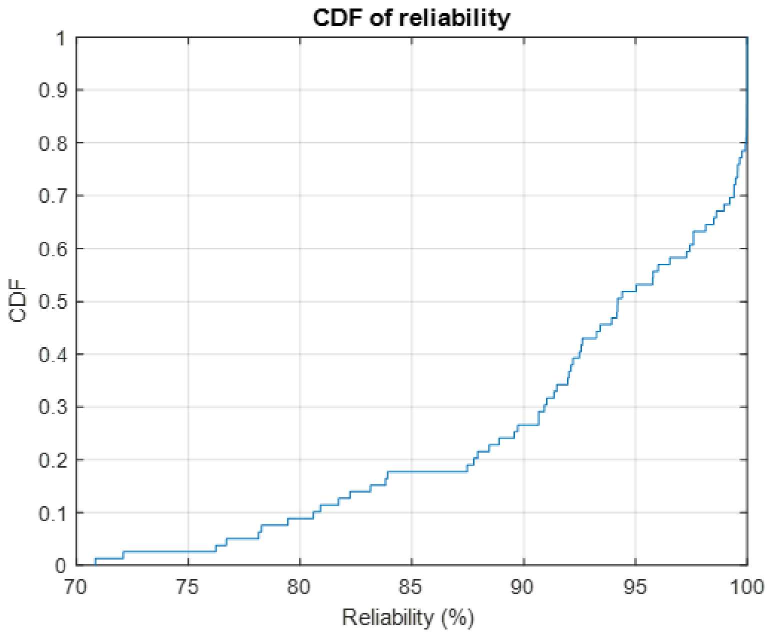


Figure 67: KR TS, CDF of reliability

Figure 67 shows the CDF of reliability. It can be seen from the figure that the target reliability of 99.9% is satisfied more than 20% of the time during the test without HARQ operation. If HARQ operation is enabled, it is expected that 99.9% reliability will be achieved most of the time.

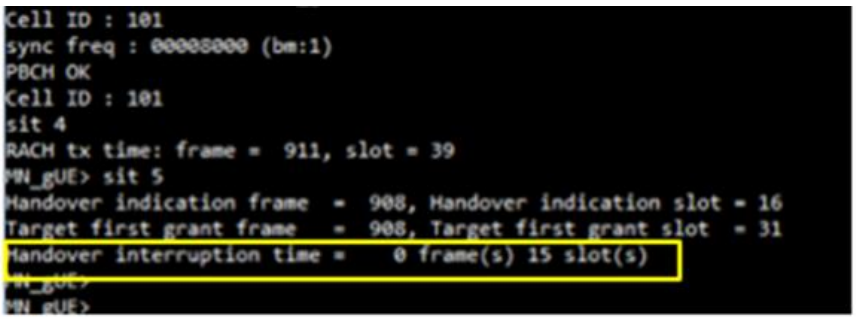


Figure 68: KR TS, Handover interruption time

As shown in Figure 68, the measured handover interruption time of 3.75 ms is calculated assuming a Transmission Time Interval (TTI) length of 0.25 ms. Although it exceeds the target handover interruption time of 2 ms, it will be further reduced when a shorter TTI length of 0.125 ms is employed as planned for future implementation.

FR TS

Several tests of the FR US Advanced Driving with Assisted Infrastructure have been performed to assess the applicability of 5G mmWave. The results rely on 4G and 5G measurements as baseline observations (TCS-FR1.1 and TCS-FR1.2) and on measurements obtained with an experimental 5G mmWave network (TCS-FR1.3 and TCS-FR1.4) deployed in FR TS.

Figure 69 shows the distribution of RSRP on 5G mmWave network one test run in Versailles where the vehicle is driving at low velocity (less than 30 km/h) for few hundreds of seconds in the vicinity of the 5G base station. As expected, this value varies depending on the distance between UE and the base station. Good network conditions indicated by RSRP higher than -90 dBm are observed when the UE is located at the road junction where 5G base station is installed. On the contrary, and a degradation is observed when the UE is leaving this area illustrated with RSPS lower than -96dBm.

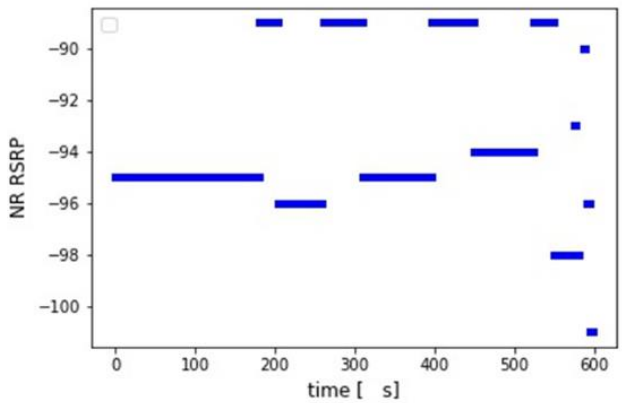


Figure 69: FR TS, RSRP on 5G mmWave during a test run

In addition, maximum throughput given by the 5G mmWave network has been assessed as displayed in Figure 70. Currently, it is on average 22 Mbps in UL and 8 Mbps in DL which is low compared to the expected value of few Gbps with such network. As such network is still experimental, it is not clear what the main limiting factors. Possible candidates could UE as no devices are commercially available and few modems could be found, network configuration as many parameters need to be adjusted. Hence, further investigation is still needed to understand and reduce the observed.

To satisfy the requirement of the FR US where higher throughput can be required in UL since vehicles need to frequently upload V2X message to a distant server and may also upload row data, higher capacity has been granted for UL communication as it is reflected in Figure 70.

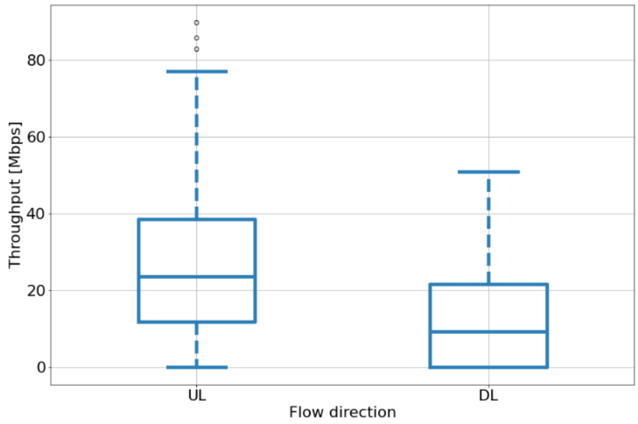


Figure 70: FR TS, Distribution of maximum throughput with 5G mmWave network measured in UL and DL

During the evaluation of FR US, a connected vehicle exchange C-ITS messages with other road entity though a MEC server installed at FR TS. Hence, Figure 71 highlights the data rate of packet for such messages transmitted between the connected an automated vehicle and the MEC server during tests of FR US. Considering all the messages (CAM, CPM and MCM), this represents few kbps of data payload which is used for assisting the connected and automated vehicle to take a decision on engaging a lane change manoeuvre. According to the performance results shown in Figure 70, network throughput is sufficient to support such message exchange.

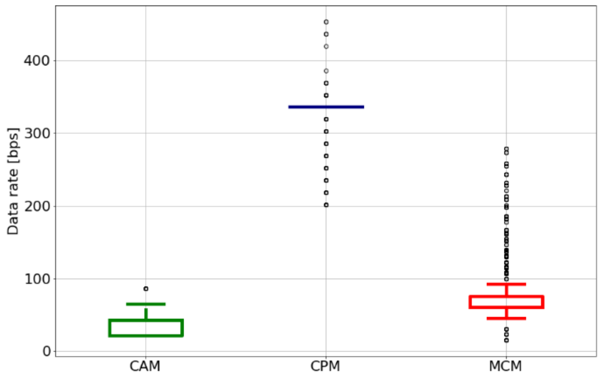


Figure 71: FR TS, Data rate of V2X message in bps transmitted from different stations

Figure 72 shows the E2E latency measure in the exchange of CAM with 5G mmWave during the different test runs. Major values lie below 50 ms and some outliers have been observed with hundreds of ms. Such performances are satisfactory for addressing the requirements. However, more robustness, i.e., no outliers, is expected to ensure a complete support for automated driving vehicles.

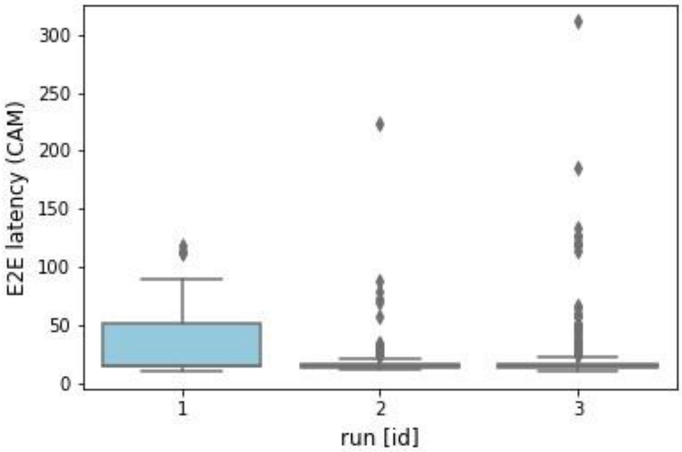


Figure 72: FR TS, E2E latency of CAM exchange measured with 5G mmWave for different test runs

4.10.2. Conclusion

The feasibility of a 5G mmWave vehicular communication system for two V2X services was investigated but its performance is behind the expectations due to its low degree of maturity. Whereas the field trials showed the potential of mmWave vehicular communications, there are several open issues that still need to be addressed before its actual implementation for commercialization. One future work is to conduct extensive field trials in different road environments such as urban roads where LOS signal blockage frequently occurs and explore whether additional technologies are required for such adverse conditions.

4.11. XBI_11: Network slicing applicability

Network slicing is a potential solution to better manage the QoS for CAM data flows and to minimise interference from background traffic. A network slice is a virtual network that is reserved for specific applications such as CAM with specific QoS requirements. The traffic in a slice is logically separated from traffic in other slices, and can be routed with higher priority to maintain the latency and reliability required by CAM services. Slicing is only tested in the NL TS. Table 60 summarizes the test cases where this solution is tested.

Table 60: Summary of UCC/US where XBI_11 was trialled

CS	CBC / TS	Use Case Category	User Story	Test Cases ID
CS_26: Network slicing	NL	Extended Sensors	CPM	NL-1.4 – 1.6
		Remote Driving	5G Positioning	NL-3.4

4.11.1. CS_26: Network slicing

NL TS

The NL TS deploys a 5G SA test network capable of RAN and core slicing. This allows for direct control over the allocation of radio resources and data plane connection to support the CAM use-cases. A local-breakout slicing setup is deployed to facilitate a direct connection to the MQTT broker on the MEC node that routes CAM messages between the UEs in two test vehicles of TNO and Siemens. Figure 73 shows the setup in which CAM messages are exchanged in a high priority CAM slice, as indicated with the blue arrows. In this scenario (test case NL-1.6), an iPerf server generates background traffic to the same UE in the TNO test vehicles as well as to other UEs such as an RSU. This background traffic is exchanged via a low priority internet slice shown as green arrows. The thicker arrows for the background traffic indicate the much larger data rates of internet (iPerf) traffic (120 Mbps) in comparison to the CAM data flows for Extended Sensors (17 kbps) or Remote Driving (16 Mbps).

Mechanisms such as relative or absolute priorities between slices are used to extend the QoS capabilities of the network. In the NL TS absolute priority is configured to guarantee the availability of capacity for a specific CAM slice over the internet slice. This means that there should always be a configurable amount of radio resources available to the CAM slice. Details on the network and slicing configuration are given in D3.7 [1], section 9. This section summarises the evaluation results of the Extended Sensors and Remote Driving slicing tests NL-1.4 to NL-1.6 in the Appendix. These tests address slicing in a single network, as part of the preparation for slice roaming that could not be completed within this project.

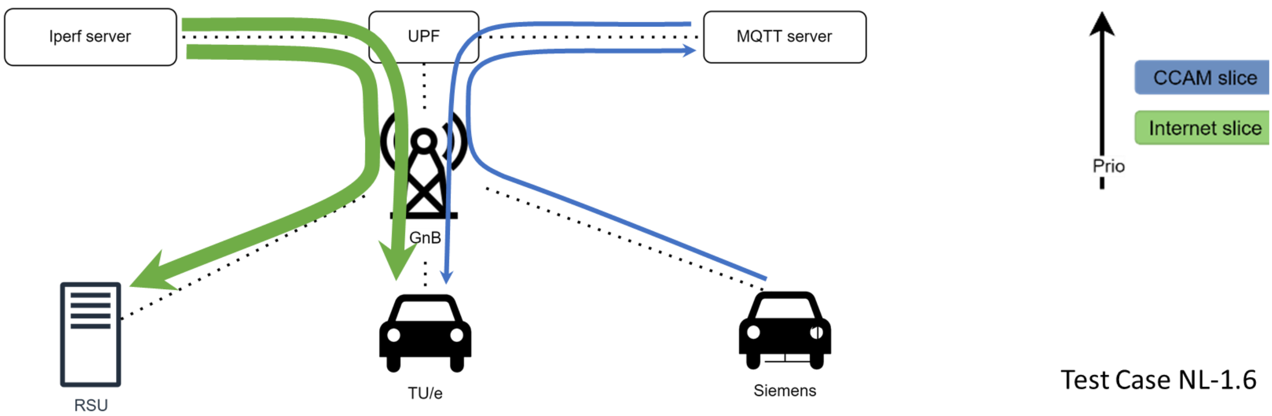


Figure 73: NL TS, Network Slicing network setup with a high priority CAM slice (blue) and a low priority internet slice (green).

To evaluate the performance of slicing on the quality of services, several slicing setups are tested in combination with background traffic flows as shown in Table 61. The E2E latency and reliability for each setup is shown in Figure 74. For priority slicing, the scheduler in the gNB for routing packets is configured by setting the 5QI values.

Table 61: NL TS, slicing test cases for the Extended Sensors use case

Test Case		Traffic flows to Test vehicle UE	High priority CCAM slice	Low priority internet slice
NL-1.4	NL1.4.1	CAM and iPerf		All traffic
	NL1.4.2		All traffic to CAM UEs	All traffic to non-CAM UEs
NL-1.5	NL-1.5.1	CAM only		All traffic
	NL-1.5.2		All traffic to CAM UEs	All traffic to non-CAM UEs
NL-1.6 (**Figure 73**)		CAM and iPerf	All CAM traffic	All non-CAM traffic

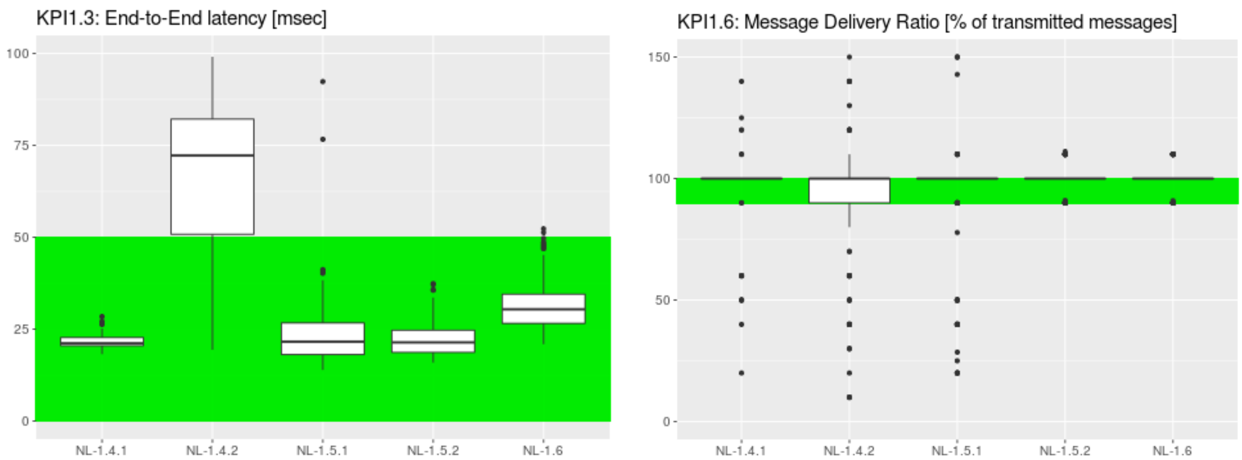


Figure 74:NL TS, slicing performance for Extended Sensors setups. E2E latency (left) and reliability (right) of CAM (CPM) message delivery between the two test vehicles via the MEC / MQTT server

When test vehicle's UE uses both CAM and internet traffic, and when both flows are combined in a single slice in NL-1.4, the schedulers on the gNB and UE cannot separate the different flows. It does not make much difference whether all flows are in the same slice (NL-1.4.1) or the background traffic to other UEs (e.g. the RSU) is separated in an internet slice while background traffic is also sent via the CAM slice (NL-1.4.2). In both cases, the gNB cannot manage the QoS required for the CAM data flow. Consequently, the CAM flow is 'flooded' by the background traffic, resulting in poor reliability and large variations in latency. Note that the most extreme values for these test cases fall outside the range shown in Figure 74 and are much worse than the other test cases. Note also that bursts in the delivery can result in much more (>> 100%) or less (<< 100%) message receptions within a single aggregation time window than the number of transmitted messages in the same time window.

In the ideal scenario where vehicles only exchange CAM data and no other traffic (NL-1.5), separating the flows is more straightforward. The scheduler at the gNB will always balance the available radio resources between the connected UE's and avoid flooding the communication to the vehicles (NL-1.5.2). Separating the CAM flow in a CAM slice as in NL-1.5.1 has a similar effect and is more or less redundant to the gNB scheduling in this idealised case. The reliability and latency significantly improve in both NL-1.5 cases compared to NL-1.4. Surprisingly, slicing (NL-1.5.1) shows more outliers in latency and reliability than in the single slice case (NL-1.5.2). This is the opposite of what was expected. During (agnostic) testing it was already observed that the UEs may show unexpected behaviour when multiple slices are used (see D3.7 [1] section 9.5.1). However, the exact cause could not be identified and resolved.

In practice, a vehicle UE will exchange a combination of high priority CAM traffic and lower priority traffic. The gNB and UE schedulers can no longer separate and manage the CAM flows, as in the idealised solution of NL-1.5, and need help from slicing. The slicing setup of Figure 73 allows to separate CAM data flows from background traffic, even to the same UE, and provide the required QoS. The average latency of 30 msec and reliability of 96% are comparable to the performance without background traffic (cf. section 4.5.4 or test case NL1.3 in the Appendix).

The gNB scheduler can balance resources for a few UEs and low data rates of CAM traffic, like in the Extended Sensors use case in NL-1.5. For Remote Driving the CAM data rate increases to 16 Mbps for the live video stream from the test vehicle UE to the remote control station. A similar test case (NL-3.4) is set up with a separate iPerf server generating background traffic to other UEs (not to the test vehicle) as defined in Table 62. Evaluation results are summarised in Figure 75. In the baseline case, without any background traffic, latency of the video stream is about 20 msec while the full data rate of 16 Mbps is maintained. In the second test case, background traffic of about 9 Mbps is added on the same internet slice causing latencies to increase significantly to 350 – 400 msec, while only a data rate of 11 Mbps can be provided. In the third case, the video stream is exchanged over a high priority CAM slice, and a QoS similar to the one of the ideal baseline cases can be provided. The full data rate can be provided for the video stream while the latency is slightly increased to 25 msec. Note that the background traffic on the internet slice has to be reduced to 5 Mbps.

Table 62: NL TS, slicing test cases for the Remote Driving use case

Test Case	Traffic flows to Test vehicle UE	High priority CCAM slice	Low priority internet slice
Baseline	CAM		CAM traffic
Internet slice	CAM		CAM + background traffic
CCAM slice	CAM	CAM traffic	background traffic

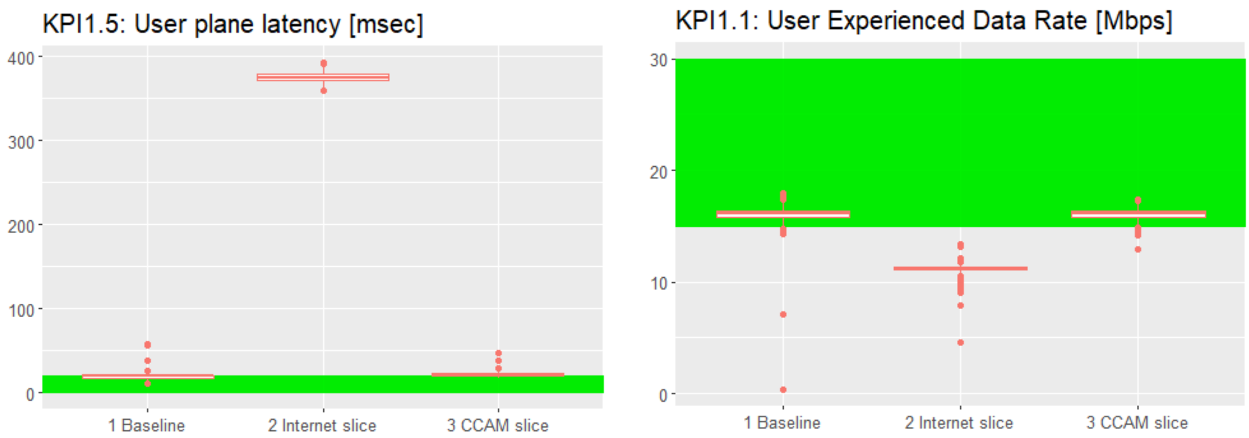


Figure 75: NL TS, slicing performance for Remote Driving setups of Table 31. User plane latency (left) and data rate (right) of CAM traffic (Video stream) from the test vehicle UE to the remote station.

4.11.2. Conclusions

Network slicing can fulfil the QoS requirements, set for both the Extended Sensors and Remote Driving US, when CAM data flows are managed in a dedicated high priority CAM slice and separated from background traffic in a lower priority internet slice.

The CAM slice should not be polluted with background traffic, because the scheduler at the gNB cannot differentiate high and low priority data streams within a slice to a UE for CAM applications.

5. CAM SERVICE SUPPORT: TARGET VS. MEASURED KPI VALUES

The previous sections presented results for both UCC/US-agnostic and specific test cases, focusing on the impact of specific configuration / deployment options, often also on the CAM domain (application level performance). In the following,

Table 63 to Table 67 are intended to give a snapshot overview of how the observed measured values of application level KPIs (TE-KPI1.1, TE-KPI1.3 and TE-KPI1.6) compare to the corresponding target values originally defined in D2.5 [3] (and subsequently updated in the Evaluation Technical Report). These tables report on the median values of the respective KPIs, for a selected set of configuration / deployment options (identified by the best KPI values achieved). The following observations are made:

- In several cases we have noticed an evolution of the Target KPI values throughout the project lifetime[7]. In particular, there are several cases where the initial requirements were proved too stringent, reflecting an overestimation of the application requirements from the network e.g., throughput requirements of the "Infrastructure-assisted advanced driving" user story from 100 Mbps / 50 Mbps (UL / DL) to 10 Mbps / 1 Mbps (UL / DL).

- The final Target KPI values in several cases appear moderate and considerably lower than the nominal capabilities (or even observed performance) of 5G networks (as shown in the example above). While this could lead to potential considerations related to the need for 5G support for these particular cases, it is important to highlight the dimension of network capacity in relation to CAM service penetration i.e., while moderate QoS requirements may in some cases be fulfilled by 4G, this expectation is based on the per-user performance; it follows that as the CAM service ecosystem evolves and penetration increases, the increased capacity of the 5G NR will be needed.

- In the vast majority of cases, Target KPI values were achieved, which is also related to the above points. However, it must be pointed out that the selected KPIs focus on steady state performance, not aimed to grasp CBC mobility effects: this is because it was impossible to have all CAM service tested under CBC mobility. Nevertheless, as noted throughout this deliverable, with the exception of LBO configurations, the vast majority of tested UCC/US was fully supported in the presence of mobility.

[7] Both initial and final values indicated in the following tables (→).

Table 63: Target values and measured values in Advanced Driving (T: Target, M: Measured)

User Story CBC/TS	TE-KPI1.1 (Mbps)	TE-KPI1.3 (ms)	TE-KPI1.6 (%)	XBI / CS
Lane Merge ES-PT	T: 0.2 / 0.2 M:0.005 UL / 0.01 DL	T: 200 E2E M: 27 UL / 14 DL	T: 99.9 M: 100	XBI_1/CS_1 XBI_3/CS_8 XBI_5/CS_14 XBI_6/CS_17 XBI_9/CS_23
Overtaking ES-PT	T: 0.2 / 0.2 M: 0.005 UL / 0.01 DL	T: 200 E2E M: 32 UL / 19 DL	T: 99.9 M: 100	
Cooperative automated ES-PT	T: 10 / 1 M: 0.0002 UL / 0.0004 DL	T: 200 E2E M: 26 UL / 18 DL	T: 99.9 M: 100	
Infrastructure-assisted FR	T: 100/50 → 10/1 M: 0.004 UL / 0.009DL	T: 50-20 → 5-200 M: 28 UL / 22 DL	T: 100 → 90 M: 100	XBI_1/CS_1 XBI_5/CS_5 XBI_5/CS_14 XBI_10/CS_25
CCA NL	T: 1 M: 0.07	T: 50 V2V / 100 V2I2V M: 35 V2V / 36 I2V	T: 95.0 M: 99	XBI_6/CS_17 XBI_9/CS_23
Cloud-assisted advanced driving CN	T: 100 / 100 M: 0.1 UL / 10.2 DL	T: 20 - 50 M: 22 UL / 24 DL	T: 90-99.99 M: 100	XBI_5/CS_5 XBI_5/CS_13 XBI_5/CS_14

Table 64: Target values and measured values in Vehicles Platooning (T: Target, M: Measured)

User Story CBC/TS	TE-KPI1.1 (Mbps)	TE-KPI1.3 (ms)	TE-KPI1.6 (%)	XBI / CS
See-what-I-see GR-TR	T: 100 UL / 50 DL → 4 UL / 4DL M: 4 UL/ 4 DL	T: 20 → 300 M: 49 UL / 43 DL	T: 99 – 99.999 M: 100 UL / 100 DL	XBI_3/CS_8 XBI_6/CS_17
5G Platooning GR-TR	T: <1 M: 0.008	T: 100 M: 67	T: 99 M: 100 UL / 100 DL	XBI_5/CS_15 XBI_6/CS_17
eRSU-assisted DE	T: 200 / 100 M: 4 I2V /0.07 V2V	T: 40 M (5G – Uu): 77 V2V / 132 I2V, single-MEC / 147 I2V inter-MEC M (5G - PC5): 66 I2V / 20 V2V	T: 99.999 M: 100 DL/100 UL	XBI_5/CS_4 XBI_5/CS_13 XBI_5/CS_14 XBI_9/CS_24
Cloud assisted CN	T: 100 / 100 M: 0.1 UL/10 DL	T: 20 - 50 M: 32 UL/ 24 DL	T: 90-99.99 M: 100 UL/100 DL	XBI_5/CS_4

Table 65: Target values and measured values in Extended Sensors (T: Target, M: Measured)

User Story CBC/TS	TE-KPI1.1 (Mbps)	TE-KPI1.3 (ms)	TE-KPI1.6 (%)	XBI / CS
HD-Maps Vehicle ES-PT	T: 100 M: 45	T: 200 V2V M: 1016	T: 99,9 M: 100	XBI_1/CS_1 XBI_3/CS_8 XBI_5/CS_15 XBI_6/CS_17
Assisted border crossing GR-TR	T: 100 / 200 → 50 UL / 100 DL M: 22 UL /375 DL	T: 100 M: 83	T: 99.999 M: 100	XBI_3/CS_8 XBI_6/CS_17
Truck routing GR-TR	T: 75 / 5 M: 14 / 14	T: 100 M: 53	T: 99.000 M: N/A	XBI_3/CS_8 XBI_6/CS_17
EDM DE	T: 200 / 100 M: 10 DL / 10 UL	T: 40 M: 51	T: 99.999 M: 92.22	XBI_5/CS_4 XBI_8/CS_21 XBI_9/CS_23
Edge processing FI	T:15 / 15 → 10 UL / 1 DL M: 2 UL	T: 100 M: 43	T: 99.990 M: N/A	XBI_5/CS_4 XBI_5/CS_10
CPM NL	T: 10 -20 UL → < 1 UL M: 0.02 UL	T: 50 M: 31 UL	T: 90 M: 96 UL	XBI_2/CS_6 XBI_5/CS_14 XBI_9/CS_23 XBI_11/CS_26

Table 66: Target values and measured values in Remote Driving (T: Target, M: Measured)

User Story CBC/TS	TE-KPI1.1 (Mbps)	TE-KPI1.3 (ms)	TE-KPI1.6 (%)	XBI / CS
Remote Control Crossing ES-PT	T: 10 / 1 M: 11 UL	T: 200 E2E M: 39 UL	T: 99,9 M: 100 UL	XBI_1/CS_1 XBI_3/CS_8 XBI_6/CS_17
Redundant network environment FI	T: 50 / 1 → 20-25 / <1 M: 20-23 UL / 0.1 DL	T: 80 M: 41 UL (RTT)	T: 99 – 99.999 M: 97	XBI_5/CS_5
5G positioning NL	T: 50 → 25 M: 32 UL / 0.6 DL	T: 50 M: 14	T: 99.500 M: 99	XBI_7/CS_20 XBI_11/CS_26
Data ownership CN	T: 100 / 100 M: 11 UL/11 DL	T: 20 - 50 M: 20 UL / 17 DL	T: 90-99.99 M: 100	XBI_5/CS_5 XBI_5/CS_13 XBI_5/CS_14

Table 67: Target values and measured values in QoS Vehicles (T: Target, M: Measured)

User Story CBC/TS	TE-KPI1.1 (Mbps)	TE-KPI1.3 (ms)	TE-KPI1.6 (%)	XBI / CS
Media Public Transport ES-PT	T: 4 / 8 M: 3	T: 200 (V2V) M: 1042	T: 99,9 M: 100	XBI_1/CS_1 XBI_3/CS_8 XBI_6/CS_17

6. LESSONS LEARNED

The technical evaluation also provides valuable lessons for future 5G deployments in cross-border areas and for CAM applications. Also, while testing and extracting KPIs and information from the obtained test data, some valuable lessons on technology readiness and testing methodology were documented.

This section is a summary of these learned lessons collected among all partners and test sites.

6.1. Lessons learned on execution and preparation of tests

6.1.1. Use of commercial networks

Many of the trials were conducted using outdoor commercial NSA networks. While the use of outdoor commercial networks prevented experimental study of peak performances (without resource sharing in the same network), the use of these production networks provided a more realistic insight of what is feasible for CAM applications in contemporary 5G networks. One consideration for future testing is to conduct the trials in different times of the day to ensure that the measurements results are captured in both busy hours and off-peak periods of the shared 5G networks.

These differences in when the user stories were executed for each test run were also affected in how the open road scenarios vary with different (real world) traffic, e.g., public buses, service trucks, and pedestrians, this, in some cases also have an impact on the observed KPI results from one test run to another. Some of these road conditions changes, affected the way in which the US is executed in practice (e.g., when video streams are triggered in remote driving). The solution to this was to target a sufficiently large number of test runs for each test case to account for these varying road scenarios and ensure statistically significant results.

Using a commercial network, as was the case with the ES side in the ES-PT CBC, implied an additional challenge from the configuration and the deployment points of view. However, at the same time, it enriched the results by revealing side effects that are important to identify so that they can be handled. One of these factors is the impact of the periodic updates of the gNBs and the cores on the network performance which have resulted in obtaining very different results for the same test case when running in different dates. Combined with this, the resource sharing with the commercial network also makes the capacity of the network unpredictable. Both effects are illustrated with the different throughput values obtained in two different dates (Figure 76) for the DL with TCP in the Old Bridge. All these details made the KPI extraction a bit more difficult, but were taken into account when identified.

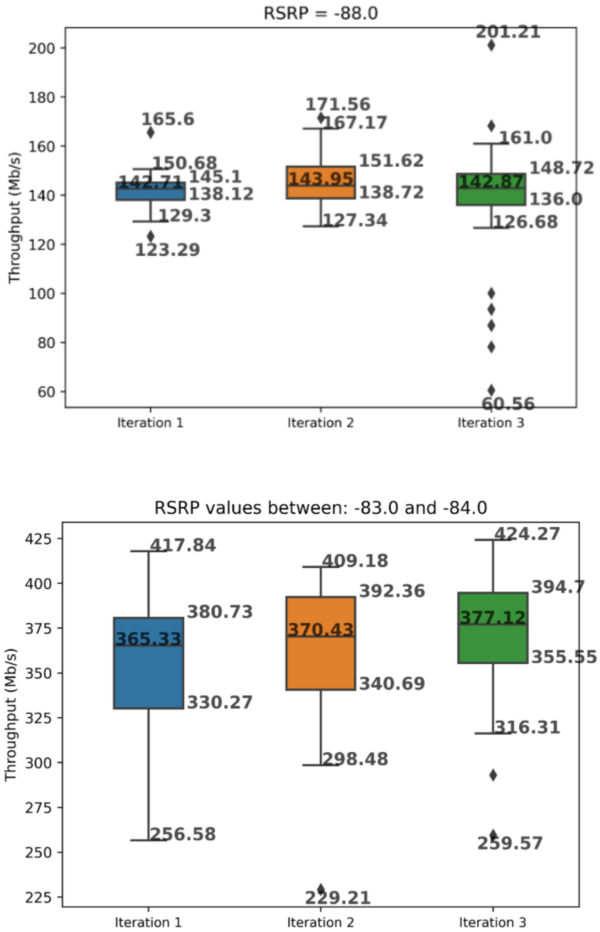


Figure 76: ES-PT CBC, comparison of the results obtained for the same test case in January 20 (up) and February 21 (bottom)

6.1.2. ES-PT CBC network asymmetry

Most of the results provided in ES-PT CBC correspond to the driving direction from PT to ES because of the problems to perform a handover in the opposite direction. As far as it was investigated, the main source of these problems is the interferences caused by the signalling metal panel on the road, just in the location preselected to perform the lane merge and overtaking manoeuvres in the New Bridge. These interferences increased significantly the latencies blocking the execution of the functions that address the CAM functions, as it can be seen in Figure 77, where the latency spike can be observed a few seconds before the handover.

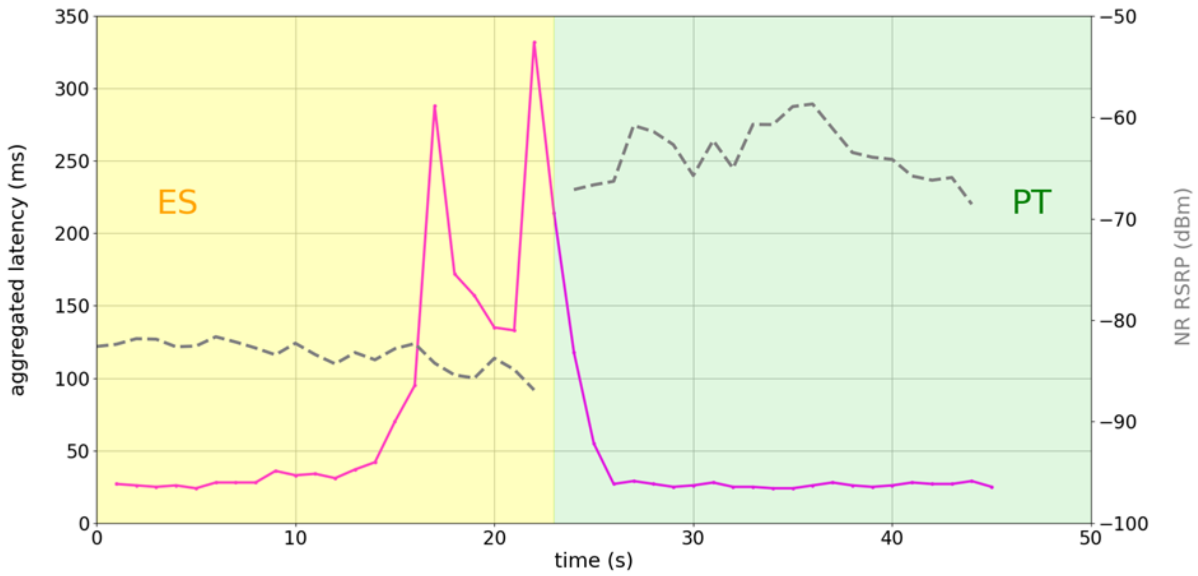


Figure 77: ES-PT CBC, peaks in the latency in UL at the application layer because of the interferences with a panel on the road

6.1.3. Radio variations

When using the 5G SA network coverage in the NL TS, the Vaarle parking test site is covered by both the KPN and TNO 5G SA networks. Reception varied strongly between pilot periods. Reception from the TNO network in September 2021 was not as good as in April 2022 for example. Such variations impede the repeatability and evaluation of pilot results. It is thus important to verify which factors may affect the tests, such as foliage in this specific case, and to select the test environment with as much Line of Sight as possible.

6.1.4. Network time synchronization

While reviewing the preliminary tests' data, time synchronization issues were present as it turns out that using standard methods such as NTP, less than 1 ms precision is difficult to obtain when long distances and mobile equipment are involved, this posed a significant challenge and was detected on these preliminary test trials and solved using the GPS receivers as an universal synchronized time source.

6.2. Lessons learned on network configuration and radio planning

As 5GMOBIX aims to showcase CAM technologies and 5G enabled automated driving, networks were optimized for availability and as low as possible interruption times, due to the fine tuning of handover parameters and cell coverage required to achieve minimum handover disruption, cell ping-pong effects can appear on UEs in which the UE jumps from one cell to another while in the edge of coverage of both cells. This fine tuning must be studied case by case to maximize coverage, minimize handover time and avoid the appearance of said "ping-pong" effects.

6.2.1. ES-PT CBC bridge specificities

For the execution of the trials in ES-PT, the handovers were planned on the administrative border between ES and PT that comprehends two bridges. These bridges are the New Bridge and Old Bridge, with a length shorter than 200 m and where the handover in both directions (ES-PT and PT-ES) was configured to happen at the same time. This short space for trialling the inter-PLMN handover caused the vehicle to enter in the handover area of the opposite direction some meters away, entering the home network with a second handover instead of remaining on the visited (roamed) network (ES-PT handover on the figure). As a result of these new negotiations with the network the modem experimented very high latencies (Figure 78). Fortunately, these undesired values appeared when the vehicle had already completed the corresponding manoeuvre (PT-ES handover on the figure).

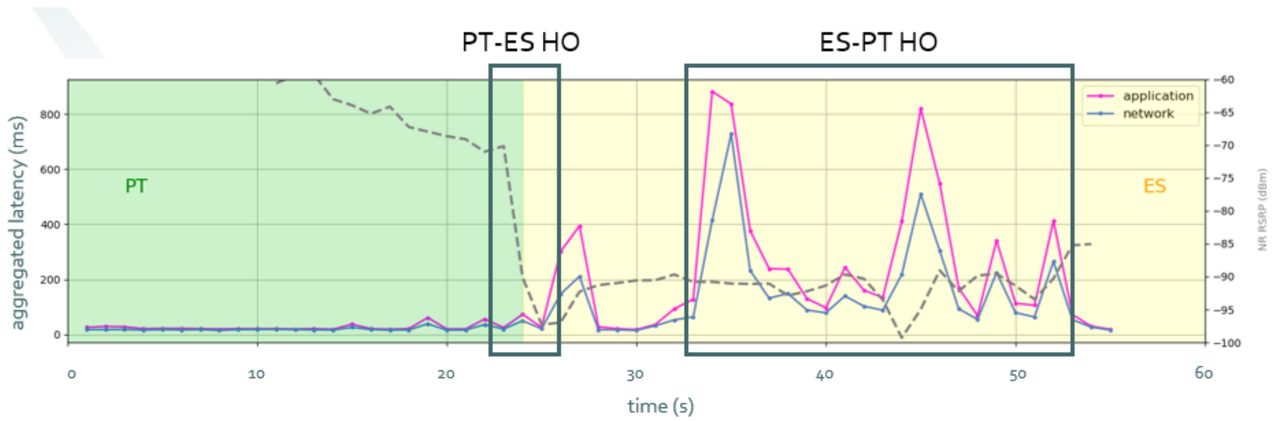


Figure 78: ES-PT CBC, peaks in the latency in UL because of the handover processes in both directions

6.2.2. NLOS and cross-cell interference (KR TS)

Field tests for two US, Tethering via Vehicle and Remote Driving in the KR TS, were successful in the sense that key functionalities such as beam switching and handover were validated and performance requirements of the US were met, showing the feasibility and effectiveness of the system. Nevertheless, two technical challenges were observed during the highway test.

The first challenge was performance degradation in some regions due to signal blockage by a road bridge located between two gNB DUs. Based on our additional ray-tracing simulation, it was confirmed that a very serious received power loss occurred in the NLOS region created by the bridge, which gives an insight that a gNB DU should be deployed lower than the bridge or much higher than and close to the bridge.

The other challenge observed during the field test was that in mmWave-band unidirectional beamforming networks, a strong interference from adjacent cells has serious interference effects on the reception of the serving cell signal, which needs to be solved by a proper frequency planning strategy or an inter-gNB DU scheduling/resource allocation mechanism.

To address these two challenges, it is necessary for an MNO to thoroughly investigate and analyse the deployment of gNB DUs and their frequency planning strategy so that the NLOS region created by a large obstacle (e.g., a road bridge) is minimized and the influence of interference from adjacent cells is mitigated.

6.3. Lessons learned on 5G devices and technology readiness level

The trials also provided some useful insights on the constraints that could be encountered when acquiring 5G devices in terms of the availability, stability, performance regional settings and provider customizations of the UE's firmware.

6.3.1. Performance variations

Other of the takeaways when extracting information and validating tests' data is that correct interpretation of tests' values must consider hardware specificities, so establishing a correct range of expected values beforehand to validate test data can be problematic without prior testing. This was remarked by the wide variation of performance that has been observed when using different devices (OBUs with M.2 modems, MiFi devices and smartphones). This can be especially problematic when fine tuning the handover values to fit different devices.

6.3.1. Stability issues

Moreover, many UE stability problems were detected when dealing with long test durations with commercial smartphones, as these terminals are designed for normal subscribers and an intensive usage during extended periods of time lead to unexpected performances or failures. 5G modems had to be restarted frequently during tests since they proved not being ready for intensive use.

6.3.1. Customization issues

Regarding provider customizations, one notable case was the testing of the FI TS multi-SIM OBU in the ES 5G network (by TELEFÓNICA). Connectivity was not possible as the commercial core network kept forcing the modem in the OBU to revert to vendor-specific APN rather that the *5gmobix* APN used for the project. The OBU did not provide APN Type configuration possibility in the admin interface, which would have allowed to force APN to remain with *5gmobix* as default. This meant that the tests had to proceed only with the 5G test network from NOS (PT) and a secondary roaming SIM card from FI. It is noted that OBU and modems from different vendors may not always be guaranteed to work when encountering such local or regional settings with constraints with some of the parameters.

6.3.2. Technology / implementation maturity

- Often 5G SA and specific bands are on the roadmap of vendors, but this support is not always solid or even implemented. A lot of time was consumed in testing several options since 5G technology implementation is still not consolidated.

- The slicing implementation on the UE's accounts can introduce unexpected behaviour when adding multiple slices on the same UE (section 4.11.1). This is probably because the UEs use some internal scheduling for transmitting the packets to the network, for which direct control is not made available. This behaviour is not seen when configuring only one slice per UE. Hence, an option was made to only configure one slice per UE in the NL TS.

- 5G technology is still at an early stage, Rel. 15 [8] is just an intermediate step, C-V2X chipsets for 5G are not ready yet and 5G-SA for mmWave is not yet defined in 3GPP. This also meant that a full 5G SA mmWave network could not be deployed in the NL TS and the tests had to deal with limited support for high-resolution angular information provided by commercial equipment. The deployed mmWave with simplified protocol stack nonetheless yields some interesting insights:

  - The use of analogue beamforming with high resolution does achieve the expected improvement in signal quality and achievable throughput. However, a strong system trade-off is identified between beam resolution and per-user performance improvement against required beam acquisition time and overall throughput decrease. This raises a need for improved beam acquisition strategies and required support for adaptive beamforming at both UE and gNB side if analogue beamforming is employed.

6.3.3. 5G SA Roaming: Release & Redirect / LBO maturity

For roaming, on the NL TS CBC, TNO and KPN chose to focus on LBO roaming with Release & Redirect functionality. Since LBO roaming requires less connections and interactions between the cores and gNBs, the LBO implementation of roaming is less complex. In that regard, 5G SA LBO roaming can be seen as one of the steppingstones towards 5G SA seamless roaming. Currently, it seems that the needed features are beyond state-of-the-art. Based on this and the efforts required to configure the Release & Redirect functionality, one could conclude that 5G SA roaming, and especially implementations trying to move towards seamless-roaming, are not yet market-ready.

Both the gNB and UE must support the functionality needed for the Release & Redirect mechanism to work and this is not trivial. Activating the Release & Redirect functionality in the gNB requires a very specific configuration. Only the most recent version of our UE's (Fibocom) firmware supports this functionality. Until now we have not been able to fully do this, even with support from the suppliers (Ericsson, Fibocom). The details of the internal workings of the commercial devices are not disclosed and the necessary information to resolve this issue is not provided. As a result, the gNB can be configured to release a UE and redirect it to another visited PLMN. However, the UE keeps re-attaching to the home PLMN, while in range of the home PLMN, and does not attach to the visited PLMN.

7. CONCLUSIONS

D5.2 reports the technical evaluation results from the analysis of the impact of roaming and handover processes on CAM functions in the inter-PLMN environments through the evaluation of the performance of a series of system configuration options as a means against service disruption. In summary our key findings include the following items:

- The S1 handover with S10 interface, along with a home routing (HR) configuration appears to provide low mobility interruption times (200-300ms) for cross border mobility across 5G NSA Option 3x deployments. This is considered adequate for several CAM applications.

- HR in 5G NSA Option 3x deployments was also found to deliver latency values acceptable to several CAM applications i.e., up to 100 ms.

- Local-break out (LBO) configuration was demonstrated to offer lower latency values, compared to HR, ripping the benefits of edge computing. However, currently available implementations support only a "break-before-make" approach (equivalent to SSC Mode 2) which incurs severe service disruption upon completion of the handover. These findings apply to both NSA and SA deployments.

- The Direct Interconnection between PLMNs in CBC environments offers significant latency benefits, especially important in the presence of HR configuration i.e., 29-51% latency reduction compared to Internet-based interconnection. The impact to control plane operations was negligible e.g., handover completion.

    - Significant benefits observed in the case of a direct interconnection between edge computing nodes, enabling end-to-end cross-border latency in the order of 15-20 ms.

- A careful service level configuration is needed in the presence of HR configuration and edge computing: name resolution should be appropriately configured to avoid inefficient routing of traffic i.e. visited PLMN to home PLMN (HR), to visited PLMN (name resolution).

- Satellite connectivity, as tested in the project, does not offer a credible alternative/fall-back to 5G, due to the substantially inferior performance.

- Multi-SIM / multi-modem solutions with link aggregation yield performance improvements compared to single-SIM setups, though not offering a wide scale solution.

    - Link selection offers inferior performance in terms of reliability, throughput and latency.

- mmWave-based positioning accuracy shown to be substantially affected by LOS/NLOS i.e., Line of sight (LOS): 0.293 [m], Non-line of sight (NLOS): 0.4 – 0.6 [m].

- mmWave connectivity suffers in several cases from implementation maturity.

- Network slicing was demonstrated to fulfil its purpose of isolating traffic and guaranteeing performance (QoS). A careful configuration is required though in what concerns the assignment of traffic flows on network slices, as traffic management cannot be differentiated on an intra-slice level.

    - Trials also demonstrated stability issues in currently available UE implementations, in what concerns network slicing support.

- In what concerns application-level configuration options:

    - Service discovery / DNS resolution measured around 40 ms. This is to be taken into account especially when considering LBO setups where a session shall be migrated.

    - Dynamically varying data rate in video streaming shown to improve reliability (5 - 20%) when network conditions degrade.

    - Widely used technologies such as MQTT or WebRTC not adequate for rapid session re-establishment often required in CBC mobility scenarios, especially in the case of LBO. Session establishment negotiations incur disruptions in the order of several seconds.

As a general remark, the above results show that the currently prevailing 5G NSA Option 3x deployments can already support a series of CAM applications in a series of use case categories e.g., advanced driving, extended sensors. The currently available S1/S10 interfaces-based roaming solution offer acceptable disruption in the presence of HR which in turn yields acceptable latencies for several applications of moderate requirements. However, the support of more stringent requirements in terms of latency, would need to be based on the availability of LBO solutions which have already been specified[8] but are not mature yet at the implementation level. At the same time, and in the presence of the currently available technology mixture, the role of application-level configurations was highlighted, especially in what concerns the interplay with underlying network configurations options e.g., routing and name resolution, session migration/re-establishment.

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