5GMOBIX

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

D3.7

Final Report on Development, Integration and Roll-out

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Control sheet

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ABBREVIATIONS

Abbreviation	Definition
3GPP	The 3rd Generation Partnership Project
5G NR	5G New Radio
AD	Autonomous/Automated Driving
AAS	Advanced Antenna System
AMF	5G Core Access and Mobility Management Function
APE	Access Provider Edge
ARFCN	Absolute Radio-Frequency Channel Number
APM	Authorities and Policy Makers
BSM	Basic Safety Message
CAV	Connected and Automated Vehicle
CBC	Cross Border Corridor
CC	Component Carriers
CAM	Connected and Automated Mobility
CAMes[1]	Cooperative Awareness Message
CIP	Communication Infrastructure Provider
CN	China
CPM	Collective Perception Message
CPRI	Common Public Radio Interface
CS	Considered Solution
CTAN	Connect Transport Aggregation Node
CTS	Centralized Test Server
C-ITS	Cellular Intelligent Transport System
CU	Centralized Unit, part of the gNB where the gNB is divided in a central - and distributed unit

[1] We deviate from the standard terminology/acronym for "Cooperative Awareness Messages" in this report, in order to align with the EC's reservation of the acronym CAM for "Connected and Automated Mobility".

Abbreviation	Definition
C-V2X	Cellular Vehicle to Everything
COTS	Commercial-off-the-Shelf
DE	Germany
DENM	Decentralized Environmental Notification Message
DNS	Domain Name System
DL	Downlink Transmission
DL-AoD	Downlink Angle-of-Departure
DL-TDOA	Downlink Time Difference of Arrival
DSRC	Dedicated Short-Range Communications
DU	Distributed Unit, part of the gNB where the gNB is divided in a central - and decentral unit
EASDF	Edge Application Server Discovery Function
EC	European Commission
EDC	Edge DNS Client
EDM	Edge Dynamic Map
EEC	Edge Enabler Client
EES	Edge Enabler Server
ENDC	Eutra NR Dual Connectivity
EPS	Evolved Packet System
ES	Spain
EU	European Union
EUHT	Enhanced Ultra High Throughput
FI	Finland
FR	France
GDPR	General Data Protection Regulation
gNB	Next generation NodeB
GPRS	General Packet Radio Service
GR	Greece

Abbreviation	Definition
GRX	GPRS Roaming eXchange
GSMA	Global System for Mobile Communications
HD	High Definition
HPLMN	Home PLMN
HR	Home Routed, for routing data back to the HPLMN from the VPLMN
HSS	Home Subscriber Server
HTTP	Hypertext Transfer Protocol
IMSI	International Mobile Subscriber Identity
IPX	IP exchange
IQN	In-Advance QoS Notification
ITS	Intelligent Transport System
KM	Kilometre
KPI	Key Performance Indicator
LBO	Local Break-Out
KPI	Key Performance Indicator
KR	Korea
LBO	Local Break-Out
LDM	Local Dynamic Map
LTE	Long-Term Evolution
LEO	Low Earth Orbit
MAC	Medium Access Control (Layer)
MCG	Master Cell Group
MCM	Manoeuvre Coordination Message
MCPC	Mobility Control at Poor Coverage
MCS	Manoeuvre Coordination Service
MEC	Multi-access/Mobile Edge Computing
MME	Mobility Management Entity
mmWave	Millimetre Wave

Abbreviation	Definition
MNO	Mobile Network Operator
MQTT	MQ Telemetry Transport Network Protocol
NDC	Networked Data Center
NodeB	Radio base station
NPE	Network Facing Provider Edge
NSA	Non-Standalone Architecture
NSSF	Network Slice Selection Function
NFV	Network Function Virtualization
NL	Netherlands
NWDAF	Network Data Analytics Function
OBU	On Board Unit
OEM	Original Equipment Manufacturer
PCI	Physical-layer Cell Identity
PGW	Packet Data Network Gateway
PHY	Physical Layer
PLMN	Public Land Mobile Network
PT	Portugal
RTT	Round Trip Time
OEM	Original Equipment Manufacturer
QoE	Quality of Experience
OSS	Operational Support System
QoS	Quality of Service
RAN	Radio Access Network
ReDR	Remote Driving
RET	Remote Electrical Tilt
RIO	Road Infrastructure Operator
ROC	Remote Operations Centre

Abbreviation	Definition
ROI	Region of Interest
RRM	Radio Resource Management
RSA	Rivest–Shamir–Adleman Cryptosystem
RSU	Roadside Unit
RSRP	Reference Signals Received Power
RSRQ	Reference Signal Received Quality
RTT	Round Trip Time
SA	Standalone Architecture
SAE	Society of Automotive Engineers
SCG	Secondary Cell Group
SD	Slice Differentiator
SFTP	SSH File Transfer Protocol
SGW	Serving Gateway
SINR	Signal-to-Interference-plus-Noise Ratio
SSC	Session and Service Continuity
SST	Slice Service Type
SU-MIMO	Single User Multiple Input Multiple Output
S-NSSAI	Single Network Slice Selection Assistance Information
SIM	Subscriber Identification Module
TAU	Tracking Area Update
TC	Technology Centre
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TR	Turkey
TS	Trial Site
UCC	Use Case Category
UDC	User Data Consolidation
UDP	User Datagram Protocol

Abbreviation	Definition
UE	User Equipment
UP	Uplink Transmission
UPE	User-Facing Provider Edge
UPF	User Plane Function
URSP	User Equipment Route Selection Policy
US	User Story
V2I	Vehicle to Infrastructure
V2X	Vehicle to Everything
VBM	Video Based Monitoring
VM	Virtual Machine
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity
WP	Work Package
WSA	Web Service Addressing
X-border	Cross-border
XBI	Cross-Border Issue
XPIC	Cross-Polarization Interference Cancelation

Executive Summary

The aim of this report is to clarify and summarize the comprehensive efforts and outcomes of the 5G CAM (Connected and Automated Mobility) infrastructure development, integration, and deployment activities in the 5G-MOBIX project across two CBCs (Cross Border Corridors) in Spain-Portugal and Greece-Turkey as well as the six local TSs (Trial Sites) in Germany, Finland, France, Netherlands, China and Korea. The challenges and lessons learned during the roll-out activities in the project are highlighted and the considered solutions are provided whenever applicable. In addition to the presentation of the deployed components at each site, this deliverable also includes detailed insights on the 5G network architecture and the data management approach adopted in the project. Furthermore, final specifications of 5G-MOBIX use-cases, KPIs (Key Performance Indicators) and common agnostic 5G performance tests are provided. The application-agnostic network performance measurements reported here, such as downlink and uplink throughput measurements, end-to-end latency, and packet loss statistics, provide an important baseline and insights for the actual CAM scenario testing and evaluations that are currently ongoing in the project.

In order to facilitate the extensive set of 5G for CAM trials, 21 vehicles were adapted and used during the project with 32 OBU (On Board Unit) deployments across all sites. In terms of advanced 5G technology deployment, all sites utilized 5G-V2X communications and among them GR-TR CBC and DE TS, FR TS, NL TS and CN TS also accommodated PC5 sidelink support. Except for KR TS, all sites applied MEC (Mobile Edge Computing) deployments in their networks. Moreover, network slicing techniques were applied in FI TS, Nl TS, CN TS and satellite deployment was used in FR TS. On the other hand, multi-SIM connectivity/roaming solutions were employed in the DE, FI, FR and CN networks. Overall, several commercial networks were part of the project with 29 gNodeB units operating in diverse frequency bands, and configurations. Regarding CAM infrastructure, all sites adopted a variety of services, such as complex manoeuvres, automated shuttle, and public transport in ES-TS CBC; see-through streaming, assisted border crossing, and truck routing in GR-TR CBC; dynamic maps and edge service discovery in DE TS; remote driving, video streaming, video crowdsourcing, HD (High Definition) mapping, and MEC service discovery in FI TS; infrastructure assisted lane change manoeuvre in FR TS; roadside assisted merging, remote driving, and cooperative collision cvoidance in NL TS; and remote driving and cloud-assisted lane change in CN TS.

In order to provide insights regarding the performance of 5G network deployments across the CBCs and TSs, a common set of KPIs were defined and captured at all sites, as reported in Section 2.8. Although straightforward numerical comparison of performance measurements would not be realistic due to the diverse nature of these networks and their conditions (e.g., antenna settings, weather conditions, distance to gNBs, terrain ...), these efforts provide key insights for the current state of 5G networks for CAM scenarios and for future 5G network deployments. The measurements indicate that when moving from the cell center to the cell edge, the reduction in performance was much higher for the uplink traffic compared to the downlink case. Overall, the measured spectral efficiency, i.e., the amount of bits per second for each Hertz used to transmit, for downlink at the cell center was on average 5 times higher compared to uplink, while that ratio goes up to 9 at the cell edge. This indicates a severe bottleneck at the cell edge in the uplink direction, while many CAM use cases, e.g., tele-operated driving, require at least as much bandwidth for the uplink as for the downlink, at all times. This calls for solutions such as deploying smaller cells, adding extra spectrum, or changing the uplink/downlink ratio in network planning.

Many 5G network technologies were adopted in the project towards addressing the identified cross-border issues for CAM. This deliverable presents those key 5G technologies and components in detail, together with the insights from the deployments and tests carried out in 5G-MOBIX, as summaried below:

- *Release with redirect* (tested with a 5G SA network at NL TS) – Current roaming agreements and the associated steering mechanisms among MNOs try to direct subscribers to a certain network by denying access to certain visited networks and updating in-time the SIM information with a preferred visited PLMN. Care must be taken to ensure that these UE-based steering mechanisms do not collide with cross-border network-based steering mechanisms and potentially cause extra disconnection time. For proper CAM operation, MNOs need to exchange basic cell information on neighbouring cells. The base stations at the borders need to be adapted with special configurations, changing over time as the network evolves.
- *S1/N2 handover through S10/N14 interface* (tested at both GR-TR and ES-PT CBCs) – In addition to the requirements for Release with Redirect case, e/gNBs at the border need to contain references to each other beyond just the channel numbers and cell ids. They must provide the involved MMEs the required identifiers so the information required for handover preparation and execution can be exchanged with the MMEs and the S10 interface between them serving as relay.
- *Multi-SIM setup for SA and NSA* (Tested in various forms at DE, FI, and FR TS) – The make-before-break approach for stateful CAM applications, enabled by the multi-SIM setup, requires more intelligence and control being placed into the OBU application as well as network-side support to minimize the impact of breaking the connection. The FR TS tests have shown that the multi-SIM solution under passive and link-aggregation modes can reduce the service interruption time down to 4.7 and 3.7 seconds respectively, from 20 seconds when using a single SIM. Furthermore, the DE TS trials of the custom multi-SIM solution have shown the viability of utilizing the GPS position to implement mobile network switching decisions for applications that can tolerate reconnections.
- *Service continuity measures* (tested at FI TS) – Different technologies at various layers can work together or replace each other to enable service continuity. The solution we tested relies mostly on the application layer protocol DNS and does not require any changes to the 5G core network. We use cloud coordinators to manage the availability of the edge servers to the clients. So, we expect that some third party, e.g., application service provider, manages edge servers across mobile networks without the need for direct MNO involvement.
- *Network slicing* (tested at NL TS) – Our tests demonstrate that slicing works and can be effectively used to guarantee connectivity for V2X traffic and applications during congestion. However, when it comes to a configuration that scales up to many simultaneous V2X slices, the dimensioning and

the distribution of the capacities between the slices serving different groups of applications and users, through absolute and relative priorities, becomes quite complex.

- *Predictive QoS* (tested at FR TS) – QoS prediction is highly dependent on the resolution of collected data that are fed into the ML models. Several iterations of deployment and testing at the FR TS have shown that the tools used for collecting data on the radio performance and geolocalising the radio measurements play a critical role in the resulting data quality. Measurements in the experimental setting show that high resolution data can lead to fine adaptations in QoS prediction, but truly impactful models should result from large-scale commercial networks with active traffic data.
- *Satellite fall-back* (tested at FR TS) – Due to its global coverage, satellite communication can help eliminate the coverage gaps in terrestrial network towards, especially for use cases that do not require extremely low latencies and for vehicles that could sustain the additional cost of a satellite module, e.g., trucks. According to the tests conducted at the FR TS, satellite communication often yielded higher latency and larger packets losses, but was proven to be useful as a back-up solution when terrestrial 5G connectivity is not available. This is especially suited for maintaining a link in the vehicle for specific applications, e.g. to continue tracking its location and to transmit specific events.
- *Local break-out roaming* (tested at both GR-TR and ES-PT CBCs) – Most of the current roaming architectures use home routed roaming, where all data traffic is routed back to the home operator. Local breakout architectures can be used to overcome this inefficiency, so that the data traffic stays with the visited network. We investigated the question of when to trigger a switch to the local network and whether this trigger should come from the network or the UE. The 5G Core system, implementing SSC mode 3, can provide a means for the network to trigger a new data session without the application losing the old connection; however this functionality is not yet available for testing with current networks and UEs.
- *Direct peering between operators* (tested at both ES-PT and GR-TR CBCs) – The main benefit of creating a local interconnect or direct peering between operators is to keep the latency low when a handover takes place to the other country. At the ES-PT corridor, a direct connection has been established between NOS and Telefonica networks, preventing the need to route traffic through a central but distant location to interconnect both PLMNs. Measurements at the ES-PT border show a round-trip time of 17 ms using the direct connection, while using an interconnect over Internet the round-trip time yields 48 ms. In case of the GR-TR site, a direct connection has been established between the two edge sites Alxandroupoli and Kartal, allowing both network and application level traffic to enjoy shortest delays (in the range of 45-50 ms) compared to an internet based interconnection, which is a significant gain for delay sensitive applications.
- *mmWave for CAM* (tested at FR and NL TS) – The key functionalities of mmWave connectivity, such as beam switching and handover, were validated and performance requirements for the CAM scenarios were met in the field tests conducted at NL TS. Nevertheless, the tests revealed severe performance degradation in some regions due to signal blockage by a road bridge located between two gNB DUs, as confirmed by additional ray-tracing simulations. Another challenge observed

during the field test was that interference from adjacent cells has serious effects on the reception of the serving cell signal. Accordingly, MNOs will need to thoroughly investigate and analyze the deployment of gNB DUs and their frequency planning strategy so that the NLOS regions created by large obstacles are minimized and the influence of interference from adjacent cells is mitigated.

During the deployment and integration activities, many critical challenges and obstacles were faced at several sites. Tight regulatory constraints on spectrum access, complicated and lengthy procedures of public institutions, restrictions on the number of allocated PLMN (Public Land Mobile Network)-IDs and ending permission dates with unexpected commercial auctions were part of the legal and regulatory issues observed on the field. Regarding the availability and reliability of the deployments, it was observed that commercially available infrastructure resources were designed in a way to avoid ping-pong effects between 5G/LTE (Long-Term Evolution) modes or cells and PLMNs, which hindered mode stabilities and steady roaming control. With the flexibility of experimentation and integration of 5G technologies on existing and newly established infrastructure resources, 5G-MOBIX CBCs and TSs enabled distinct opportunities and novel solutions for the challenges that were faced during the deployment of 5G CAM applications. Overall, globally integrated efforts on defining and realizing 5G deployment activities provided valuable insights that will serve to identify and respond to standardisation gaps as well as strengthen the efforts towards next generation CAM applications.

1. INTRODUCTION

1.1. About 5G-MOBIX

5G-MOBIX aims to showcase the added value of 5G technology for advanced CAM use cases and validate the viability of the technology to bring automated driving to the next level of vehicle automation (SAE L4 and above). To do this, 5G-MOBIX demonstrates the potential of different 5G features on real European roads and highways and create and use sustainable business models to develop 5G corridors. 5G-MOBIX also utilizes and upgrades existing key assets (infrastructure, vehicles, components), and ensures the smooth operation of 5G within a heterogeneous environment comprised of multiple incumbent technologies such as V2X.

5G-MOBIX executes CAM trials along cross-border (x-border) and local corridors using 5G core technological innovations to qualify the 5G infrastructure and evaluate its benefits in the CAM context. The project also defines deployment scenarios and serves to identify and respond to standardisation and spectrum gaps.

In D2.1 [1], the required features to enable advanced CAM deployments on the 5G-MOBIX user stories are thoroughly investigated. The expected benefits of 5G for these identified user stories are planned to be tested during trials on 5G corridors in different EU countries as well as in Turkey, China, and Korea.

The trials allow 5G-MOBIX to conduct technical and business evaluations and assessments as well as perform cost/benefit analysis. As a result of these evaluations and international consultations with the public and industry stakeholders, 5G-MOBIX aims to identify new business opportunities for the 5G-enabled CAM and propose recommendations and options for its deployment.

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

1.2. Purpose and Structure of the Deliverable

The main objective of this deliverable is to present the details of the 5G for CAM trial sites and cross-border corridors deployed across Europe and at two locations in Asia as part of the 5G-MOBIX project. To that end, this deliverable jointly serves the purpose of two Work Packages (WPs), namely, *WP2: Specifications* and *WP3: Development, integration and roll-out*.

In the case of WP2, this deliverable provides a venue for reporting updates to the specification of 5G-MOBIX use cases, 5G network architectures, CAM infrastructures and applications, test vehicles and key performance indicators (KPIs). These aspects were initially outlined in WP2 deliverables D2.1-D2.5 (submitted in M14) [1] [2] [3] [4] [5] and provided the early baseline specifications for WP3 activities. Within the WP3, all the necessary ingredients of realistic 5G network testing for CAM scenarios were developed, deployed, and integrated at each of these trial sites, consisting of connected and automated vehicles, 5G network infrastructure, roadside infrastructure and CAM applications, and measurement framework to support the trialling activities. As the final output of WP3, this deliverable provides the outcomes of the deployment and verification activities on all these components at 5G-MOBIX pilot sites. Moreover, deliverable highlights some of necessary updates and deviations from the initial WP2 specifications to ensure the alignment across sites and rigorous consideration of cross-border issues.

Accordingly, the rest of the document is structured as follows:

- **Section 2, 5G-MOBIX Final Specs & Deployment Overview,** details deployment characteristics and technical specifications regarding data management, KPIs.
- **Section 3, 5G Network Architecture,** presents the 5G network features and architectural components that are employed in the project to help address cross-border issues and provides the learnings and insights from the conducted tests.
- **Sections 4-5, CBC Development, Integration & Roll-Out,** gives an overview of CBC trial sites detailing deployed components, measurement tools and verification results.
- **Sections 6-11, TS Development, Integration & Roll-Out,** summarizes achievements of DE, FI, FR, NL, CN, KR trial sites clarifying deployed components, measurement frameworks, verification results and confronted challenges.
- **Section 12, Conclusion & Recommendations,** underlines key challenges and best practices for cross-border deployments as well as possible future directions.

1.3. Intended Audience

The deliverable *D3.7 – Final Report on Development, Integration and Roll-out* is a public deliverable and it is addressed to any interested reader. However, it specifically aims at providing the 5G-MOBIX consortium members, as well as the wider community of related EU projects members and followers, with the design choices and deployment considerations addressed in 5G-MOBIX regarding the '5G for CAM' infrastructure components, protocols, applications, and measurement platforms.

2. 5G-MOBIX FINAL SPECS & DEPLOYMENT OVERVIEW

2.1. General Deployment Objectives and Characteristics

The main outcome and impact of 5G-MOBIX are to set up the foundations for the deployment of 5G CAM services and applications in cross-border areas. In order to showcase the effect of 5G for CAM applications, two cross border corridors (Spain – Portugal and Greece – Turkey) have been selected alongside with six local trial sites in Europe (France, Germany, Finland, and Netherlands) as well as Asia (China and South Korea). The main purpose of the CBC 5G corridor rollouts and deployments is to provide state-of-the art trial sites where the performance of stringent 5G enabled CAM applications can be evaluated in cross-border conditions.

The partnership of the ES-PT cross-border corridor is composed of several complementary stakeholders that cover the complete value chain including vehicle manufactures as well as research institutions. It provides a realistic soft-border-crossing environment for the testing of 5G for CAM across the EU countries. On the other hand, the GR-TR cross-border corridor constitutes the south-eastern border of the European Union providing a challenging geopolitical environment due to the existence of actual, physical borders, where customs agents perform rigorous border checks. This demonstrates the level of support provided for the deployment of CAM use cases at EU border conditions. Additionally, the six local 5G-MOBIX trial sites offer different user stories, environments and circumstances, using a variety of equipment to complement the CAM platforms, application development efforts and infrastructure enhancements in CBCs. Moreover, the local TSs contribute with tangible HW and SW components to the deployments and operation of the CBCs.

An overall view of the 5G-MOBIX sites in Europe is depicted in Figure 1, together with the selected 5G features and characteristics at each site. This allows a large variety of CAM environments and 5G configurations to be deployed and tested in the project. Those features include the combination of SA and NSA networks, multi-modem/multi-SIM solutions, near-edge and far-edge deployments, edge service discovery, SA network slicing, 5G localisation, and satellite network integration. Particular details of these 5G features, including the related standards, architecture, and insights from 5G-MOBIX tests, are provided in Section 3.

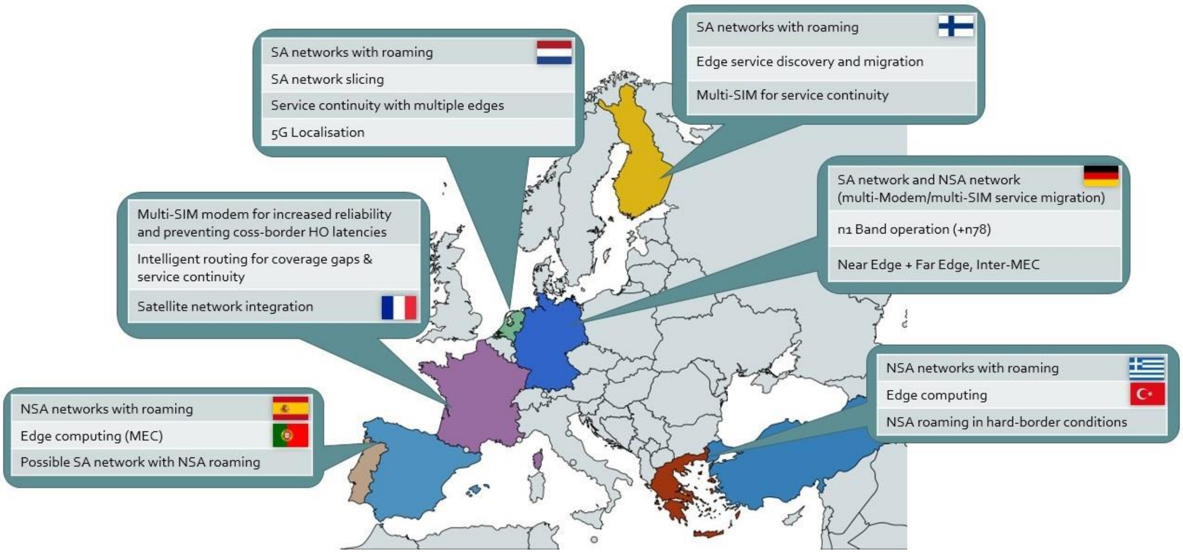


Figure 1: Key 5G Network Characteristics and Features of the 5G-MOBIX Cross-Border Corridors (ES-PT and GR-TR) and Trial Sites (DE, FI, FR, NL) in Europe

2.2. 5G-MOBIX Final Use Case Specification

While an initial definition and specification of use-cases was presented in deliverable D2.1 [1], some user-stories were subdivided in the course of the project, for the sake of organization and to focus on the specific contributions to the overall objectives. Table 1 presents a global overview of the use-stories addressed by the project, according with the subdivision. For reference, the first number refers to the use-case category, while the second number refers to the user-story (as defined in D2.1). In cases where subdivisions exist, because multiple scenarios are planned, or different technical components are addressed, these are represented by letters. For instance, US#1.1.a refers to the Advanced manoeuvres user-story (1), the complex manoeuvres being tested in ES-PT (1), and the lane merge manoeuvre (a). For each user-story a set of distinctive features is presented, describing the focus of the use-story and, where relevant, its distinction from others. The numbering is used throughout this and other deliverables.

Table 1: 5G-MOBIX Final Use Case Specifications

Use-case category	#US numbering	User-story	Distinctive feature
Advanced driving	US#1.1.a (ES-PT)	Complex Manoeuvres in Cross-Border Settings: Lane Merge for Automated Vehicles (LaneMerge)	• User story performed in a real soft border • Enhanced safety for autonomous manoeuvres at high speeds • Focused on data sharing between connected vehicles, infrastructure and autonomous vehicle with the use of a Communication Unit with 5G capabilities and through a MEC Node.

	US#1.1.b (ES-PT)	Complex Manoeuvres in Cross-Border Settings: Automated Overtaking (Overtaking)	• User story being performed in a real soft border • Enhanced safety for autonomous manoeuvres at high speeds • The purpose of this use case is to extend the 360º perception layer of the automated vehicle by integrating communication capabilities in the different vehicles of the scenario by using 5G OBU.
	US#1.2 (FR)	Infrastructure-Assisted Advanced Driving (AssInfrastructure)	• Focus on building the intelligence in the infrastructure for different configurations (MEC and cloud) • Predictive QoS under networks with different capacities (cmWave, satellite communication). Flow priorisation and quality control. • Test performance continuity with multi-SIM connectivity solutions with link-bonding capabilities. Test performance under mmWave 5G networks
	US#1.3 (NL)	Cooperative collision Avoidance (CoCA)	• Focus on precise collision risk detection and calculation. • Specific approach of NL TS in testing of Manoeuvre Coordination Service (MCS). • Comparison of decision making in-vehicle (vehicle negotiation) and in the infrastructure (giving advice to vehicles) • Communication between vehicles connected to different networks in NL TS; • Testing in full highway environment to benefit ES-PT compared to border-crossing site.
	US#1.4 (CN)	Cloud Assisted Advanced Driving (CloudAssisted)	• Use of cloud server with 5G NR for the leading vehicle • Testing different 4G/5G MNOs, OBUs and handover scenarios.
	US#1.5 (ES-PT)	Automated Shuttle Driving Across Borders: Cooperative Automated System (CoopAutom)	• User story being performed in a real soft border. • Enhanced safety for vulnerable road users in the area of action of the shuttle. • Last-mile autonomous shuttles operating in interurban areas. • 5G allows uninterrupted, low latency communications that enable the vehicle to be notified in real-time of the presence of users at risk of collision.
Platooning	US#2.1.a (GR-TR)	Platooning with "See What I See" Functionality in	• Platooning using 5G instead of DSRC (Dedicated Short-Range communications) for the 4K video streaming application "See-What-I-See".

		Cross-Border Settings (SeeWhatISee)	• Low latency video streaming for increasing the truck driver's safety with the provision of an improved front-view situational awareness • Application-level handover management while the platoon crosses the borders and a different MNO exists.
	US#2.1.b (GR-TR)	Platooning through 5G Connectivity (5GPlat)	• Platoon coordination enabled by 5G communication instead of DSRC (Dedicated Short-Range communications)
	US#2.2 (DE)	eRSU Assisted Platooning (AsseRSU)	• Comparison of platooning decision making in-vehicle (vehicle negotiation) and in the infrastructure (giving advice to vehicles) • Hybrid networking
	US#2.3 (CN)	Cloud Assisted Platooning (AssCloud)	• Use of cloud server with 5G NR for the leading vehicle • Testing different 4G/5G MNOs, OBUs and handover scenarios.
Extended Sensors	US#3.1.a (ES-PT)	Complex Manoeuvres in Cross-Border Settings: HD Maps (HDMapsVehicle)	• User story being performed in a real soft border • Enhanced safety for autonomous manoeuvres at high speeds. • Vehicles are able to record the dynamic events they encounter and send large amounts of information to the cloud via 5G to update the HD map of the other vehicles in the nearby area.
	US#3.1.b (ES-PT)	Public Transport: HD Maps (HDMapsPublicTransport	• User story being performed in a real soft border • Use of a commercial bus in a real environment (real passengers, covering the real route) • Using a vehicle with a periodic route as a sensor capturing data from the roads to update HD Maps.
	US#3.2.a (GR-TR)	Extended Sensors for Assisted Border-Crossing (AssBCrossing)	• Enhanced Mobile Broadband (eMBB) for streaming video data from multiple cameras for license plate recognition and video anomaly • Threat assessment of incoming vehicles, and autonomous redirection for further inspection. • URLLC capabilities needed for customs personnel protection and autonomous breaking of the truck.
	US#3.2.b (GR-TR)	Truck Routing in Customs Area (TruckRouting)	• Perception is placed to the cloud not to the vehicle itself for truck routing - path following application
	US#3.3 (DE)	EDM-Enabled Extended Sensors	• Demanding and scalable processing performed at the MEC for data fusion and EDM ROI filtering,

		with Surround View Generation (EDM)	including the challenge of MEC handover dealing with EDM overlaps. • Roaming scenario requires migration of CAM services among MEC infrastructure; • Generates an Edge Dynamic Map (EDM) and a 3D surround view, (Applicable to other user stories to increase the awareness.
	US#3.4 (FI)	Extended Sensors with Redundant Edge Processing (EdgeProcessing)	• Integration of dynamic MEC service discovery and migration with 5GC
	US#3.5 (NL)	Extended Sensors with CPM Messages (CPM)	• Addressing V2X continuity, SA Roaming latency and neutrality regulation cross-border issues • Tests of messages exchange between different edges for optimizing volume of messages based on actual requests; • Test performance continuity with handover between PLMNs; • Assessment of the impact V2X discontinuity in safety assessment; • Tests of messages exchange between different edges for optimizing volume of messages based on actual requests;
Remote Driving	US#4.1 (ES-PT)	Automated Shuttle Driving Across Borders: Remote Control (RCCrossing)	• User story being performed in a real soft border • 5G connectivity provides the necessary ultra-low latency and continuity in communications to drive remotely from a Remote Control Centre the last-mile automated shuttle, even in cross-border environments. • The developed and integrated MEC applications for complementing the CAM infrastructure.
	US#4.2 (FI)	Remote Driving in a Redundant Network Environment (RedundantNE)	• Redundant multi-PLMN or multi-SIM approach. Initially testing multi-SIM handover with between NSA-NSA networks, but with SA upgrade, would also test NSA-SA, SA-NSA, SA-SA • Testing service continuity with SA-SA roaming with local breakout architecture
	US#4.3 (NL)	Remote Driving using 5G Positioning (5GPositioning)	• Use of slicing to isolate video streaming, control of the vehicle; • Ise of 5G positioning correction signals (tested); • mmWave for accurate positioning.
	US#4.4 (CN)	Remote Driving with Data	• Use of data ownership mechanism

		Ownership Focus (DataOwnership)	• Testing different 4G/5G MNOs and handover scenarios.
	US#4.5 (KR)	Remote Driving using mmWave Communication (mmWave)	• Providing high quality and low latency multi-video streaming (Front, Left, Right, Rear and Surround View) to the human operator • RCV will be used like the following use cases; • remote support when out of ODD due to rain, snow, fog, or other sudden environmental condition changes • passing through a region outside of ODD • Support for mmWave • Support for high mobility
Quality of Service	US#5.1 (ES-PT)	Public Transport: HD Media Services and Video Surveillance (MediaPublicTransport)	• User story being performed in a real soft border • The ability to transfer high-quality online content with low latency allowed by 5G is key to giving public transport companies a real-time monitoring system of vehicles' visual environment.
	US#5.2 (KR)	Tethering via Vehicle using mmWave Communication (Tethering)	• Providing enhanced user experience such as 4K video streaming, high-speed WiFi, VR/AR, gaming to passengers in a vehicle (e.g., bus) • Support for mmWave • Support for high mobility

2.3. Deployed Components Overview

This section provides an overview per CBC/TS of all the components (networks, OBUs, vehicles, CAM infrastructure) that were developed, tested, integrated and deployed as part of WP3 work, to create the CBCs/TSs used for the 5G-MOBIX trials.

Table 2: Summary of vehicles and OBUs deployed

CBC/TS	Vehicles Used	Number of Deployed OBUs
ES-PT	1 Shuttle EV Bus (L4) 1 Citroën C4-Picasso (L4) 2 Citroën C4-Picasso (L0) 1 Volkswagen Golf (L4) 1 ALSA bus (L0) 1 PT connected vehicle (L0)	10
GR-TR	2 Ford-MAX (L4)	2
DE	1 Volkswagen Passat (L1) 1 Volkswagen Tiguan (L1) 1 Toyota Prius (L1)	4

FI	1 Renault Twizy (L4) 1 Ford Focus (L1)	2
FR	1 Renault ZOE (L4) 1 Renault Scenic (L1)	5
NL	1 Volkswagen Touareq (L4) 2 Toyota Prius (L4)	6
CN	1 SDIA (L4)	1
KR	1 Renault XM3 (L4)	2
Total	**21 vehicles**	**32 OBUs**

Table 3: Advanced 5G technologies deployment comparison

Technology / Site	ES-PT	GR-TR	DE	FI	FR	NL	CN	KR
C-V2X	5G-V2X	5G-V2X (PC5 support)	5G-V2X (PC5 support)	5G-V2X	5G-V2X (PC5 support)	5G-V2X (PC5 support)	5G-V2X (PC5 support)	5G-V2X
MEC Deploy-ment	Yes, Nokia solution	Yes, Ericsson solution	Yes, near edge & far edge	Yes, MEC Service Discovery	Yes, Far/ Cloud Edge	Yes, MEC Discovery SSC M3	Yes, China Mobile solution	No
Network Slicing	No	No	No	Yes	No	Yes	Yes	No
Roaming	Cross-border	Cross-border	Multi-SIM in NSA/SA	Multi-SIM in NSA/SA, Lab SA-SA	Multi-SIM in NSA	Virtual cross-border	Multi-SIM in NSA/SA	No
Satellite Deployment	No	No	No	No	Yes	No	No	No

Table 4: Overview of 5G-MOBIX networks

CBC/ TS	Type	Commercial/ Test Components	Num. gNBs	Freq. Bands	Slicing
ES	NSA	Commercial: Transport network, 1x 4G RAN (MOCN) Test: 1x Core, 5G RAN, MEC	4	800 MHz (LTE B20), 1800 MHz (LTE B3) 2600 MHz (B7), 3.7 Hz (5G NR n78)	No
PT	NSA (SA)	Commercial: IP and Transport Network Test: 1x RAN, 1x Core, MEC	3	1800 MHz (LTE B3), 3700 MHz (5G NR n78)	No
GR	NSA	Commercial: IP and Transport Network Test: 1x RAN, 1x Core	1	LTE B7 (2600) 20MHz, NR n78F (3500-3600)	No

TR	NSA	Commercial: IP and Transport Network Test: 4x RAN, 1x Core	3 (+1)	LTE B7 (2600) 20MHz, NR n78G (3600-3700)	No
DE	NSA/SA	Commercial: 2x NSA Core + 2x RAN, 1x MEC Test: 1x SA Core + 1x RAN, MEC	2	NSA: 2.1 GHz (5G NR n1) + 800 MHz (LTE B20), 900 MHz (LTE B8), 1800 MHz (LTE B3) 3.6 GHz (5G NR n78) + 1800 MHz (LTE B3), 2600 MHz (B7) SA: 3.7 - 3.8 GHz (n78)	No
FI	NSA/SA	Commercial: 2x NSA Core + 2x RAN Test: 2xRAN, 2xCore, MEC	2	2600 MHz (B7), 3.5 GHz (n78)	Yes
FR	NSA	Commercial: 1x Core Test: 3x RAN + 2x Core, 2x MEC	3	700 MHz (4G), 800 MHz (4G), 1800 MHz (4G) 2100 MHz (3G/4G), 2600 MHz (4G) 3500 MHz (5G), 3700-3800 MHz (n77), 26 GHz (n258)	No
NL	SA	Commercial: 1x 4G RAN (MOCN), 1x 4G transmission Test: 3x 5G RAN, 3x Core, 3x MEC	6	3.7 GHz (5G NR n78) 27 GHz (5G NR n258), LTE: 800 MHz (LTE B20), 1800 MHz (LTE B3)	Yes
CN	SA	Commercial: 2x Core (China Mobile, China Unicom) Test: 2x RAN 2x MEC	3	3.5GHz(n78), 4.9 GHz(n79) 2.6GHz(n41)	Yes
KR	NSA	Test	3	22-23.6 GHz	No
Total			**29**		3+3

Table 5: CAM Infrastructure Components at Cross-Border Corridors and Local Trial Sites

CAM Infrastructure Components						
CBC/TS	**Road sensors**	**RSU**	**RSU MEC (Far edge)**	**MNO MEC (Near edge)**	**Cloud**	**CAM Services**
ES/PT	Traffic Radar, Pedestrian detector, 5G smartphones, ITS Centers, Remote Control Center, Cameras	Yes	No	Yes	Yes	Complex Manoeuvres, Automated Shuttle, Public Transport
GR/TR	Camera	Yes	No	Yes	Yes	See-through streaming, assisted

						border crossing, truck routing
DE	Camera, traffic analysis, road condition	Yes	Yes	Yes	Yes	EDM, GDM, Edge MANO, edge service discovery
FI	No	No	No	Yes	Yes	Remote driving, video streaming, video crowdsourcing, HD mapping, MEC service discovery
FR	Cameras, LiDAR	No	Yes	Yes	Yes	Infrastructure assisted lane change manoeuvre, different MEC Deployment options
NL	Cameras	No	Yes	Yes	Yes	Roadside assisted merging, Remote driving, Cooperative Collision Avoidance
CN	Data center, Remote Control Center	Yes	No	Yes	Yes	Remote driving, Cloud-assisted lane change

2.4. Data Management

The main concern for Data Management was driven by usefulness, value and usage of data themselves. Therefore, efforts have been made to describe the data, to ensure their quality and uniformity, so that they can be shared and used as efficiently as possible. The Centralised Test Server (CTS), the methods and the tools involved in the data management process allowed achieving this goal.

The CTS is a unique platform to upload, share, store and browse the data and statistics, allowing the evaluators to compare and to work with harmonized data. The CTS unifies the way the test data is transferred and guarantees that all mandatory metadata are provided to identify precisely any shared data created during trialling activities. The core of the CTS is an application server running the back-end (CTS main application) and exposing the front-end (CTS web interface). The CTS also has a REST API to facilitate the automation of the upload and download processes. The resulting Centralised Test Server platform and associated tools for transferring data enable an optimised management of test data collected during 5G-MOBIX test sessions and ease the identification of research data that will be shared under Open Research Data Pilot.

More details about CTS and Data Management can be found in deliverable "*D3.5 - Report on the evaluation data management methodology and tools*" [6].

2.4.1. Overview

- CDF (Common Data Format)

The Common Data Format has been defined, for each type of data logged during test runs, across all Trial Sites, in order to specify which data are relevant for the evaluation and uniformize them for their processing (see D3.5 for further details).

- DQCT (Data Quality Check Tool)

The Data Quality Check tool has been created to help data provider checking and building data logs assuring the required level of quality of the data logged in common format log files. This tool is also used to create a quality report on the test data archives, joined to the archive to help evaluators in their work (see D3.5 for further details).

- Statistics Script

The statistics calculation tool has been developed to compute measurements statistics and KPI, according to data log type. This tool also parses and stores raw data from data logs into a database, along with statistics results, allowing and easing data digging and requests (see D3.5 for further details).

- Test Data Description

A XSD template has been developed to allow generating test data description files containing all necessary metadata and useful information about test run conditions and log files in order to fulfil evaluators needs (see D3.5 for further details).

- Test Data Builder

This tool has been developed for building test data archives containing all data collected during a test run. This tool automatically generates test data description file, checks data quality according to common data format, and generates a quality report, added to the archive. Once archive ready, this tool uploads it to the CTS (see D3.5 for further details).

- CTS (Centralized Test Server)

A centralized platform has been developed which aims to collect and store the data from the trial sites and to allow the evaluators to browse, access and download data. The CTS allows also calculated statistics browsing and downloading (see D3.5 for further details).

Figure 2 shows the global workflow, from collecting and checking data to packaging and uploading to CTS.

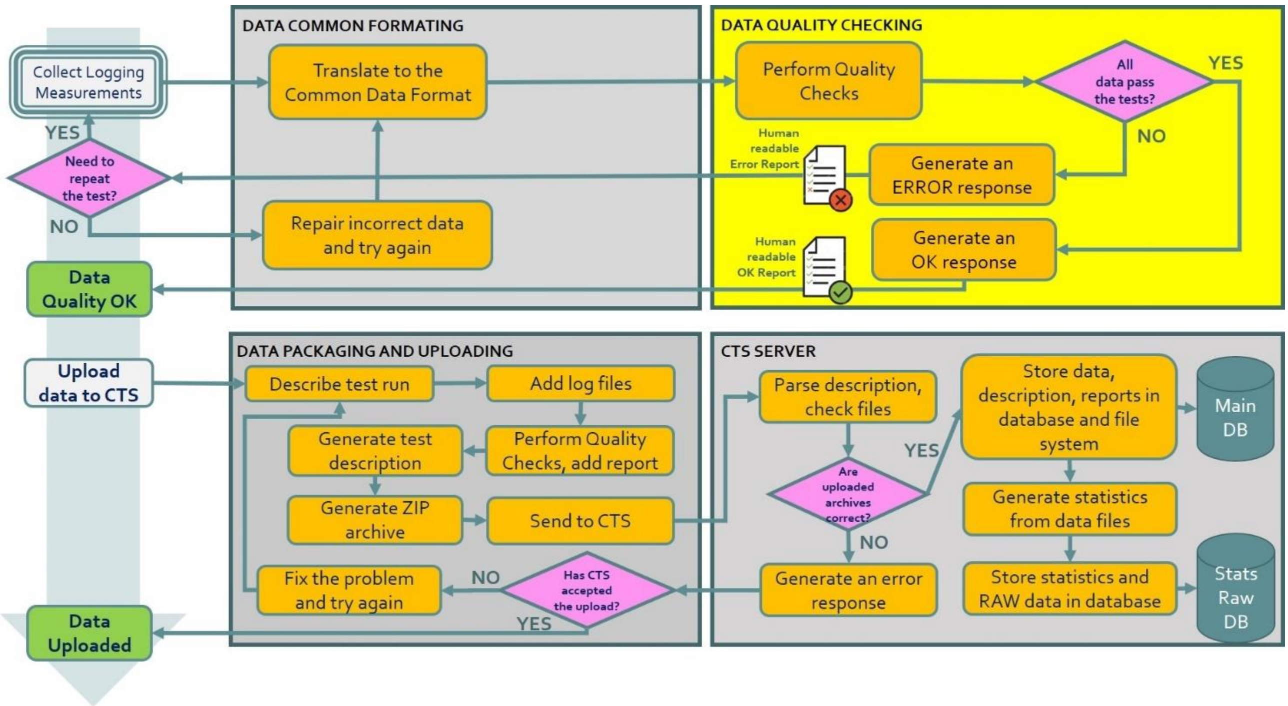


Figure 2: Global data workflow

2.4.2. Centralized Test Server

The CTS is accessible via this URL[2]. The platform is designed according to a three-tier architecture (presentation, processing, data). The presentation layer is a web application, the processing layer a Java server, and the data layer a PostgreSQL database and a filesystem storage. The web client application (front-end) is developed in Angular, runs under a Nginx server, and it is in communication with the server using a REST API. The application server (back-end) is developed with Java Spring Boot, runs under a Tomcat server, and is in communication with the PostgreSQL database. The REST API is secured with JSON WEB TOKEN (JWT). This concept allows users to enter their username and password to obtain a token to access a specific resource for a specific period.

CTS web interface, back-end, database and storage are located in the Microsoft Azure cloud, on servers located in France. It is accessible in a secured way, using credentials created per user by the administrator (AKKA). CTS website allows to browse and download uploaded test data, read data details and quality check status, browse and download statistics calculation results, and follow data uploading and processing status.

[2] https://cts-5g-mobix.francecentral.cloudapp.azure.com

CTS provides a REST API, which can be triggered directly or using Swagger. It makes it possible to give access to all the public resources available in the CTS. Those interfaces require user authentication, using CTS credentials. This REST direct access can be used for partners willing to use automatic procedures, Python scripts for instance, what cannot be achieve across web interface.

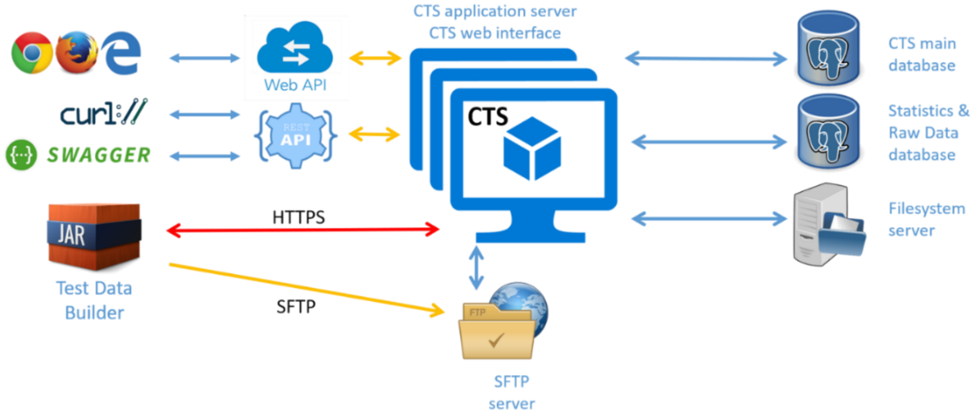


Figure 3: Centralized Test Server architecture

CTS uses two distinct databases. First one contains test data and data files description tables, tasks and users management tables, trial sites and internal data tables. Second one contains test data description in relation to main database, statistics calculations and raw data from test data files. This database is accessible to evaluators willing to dig in statistics or raw data using queries. Figure 3 shows CTS architecture and APIs.

The CTS Web interface is composed of the following pages:

- Test Data web page, listing available test data archives uploaded to the CTS
- Task page, displaying the status of all uploads
- Statistic page, displaying all the values for all the data files found in all test data archives

Details about various elements are accessible on clicking them, and displayed in popup windows:

- Test data description, which is set using the Test Data Builder
- Data files contained in each archive (can also be downloaded individually, as well as test data description, or quality check report)
- Statistics calculated on a test data (all data files)
- Statistics of a selected data file

2.4.3. Test Data Builder Tool

This standalone Java application is designed to help data managers to create test data archives with accurate and complete description and to upload these archives to the CTS. The main user interface form is focused on collecting test data description, then the user can add as many data files as needed, each one with its description.

The DQCT is embedded in the Test Data Builder and is called each time a data file is added. When the archive creation is launched, the Data Builder calls DQCT to generate the complete quality report which is referenced in the test data description file and is joined to the archive.

DQCT needs format files defining data logs expected structure, content, types, limits, etc. These files are used as a template for quality check verification and report generation. Default format files compliant with Common Data Format are provided with the Test Data Builder. However, the data manager can define its own format files and add them to existing ones, allowing DQCT and Data Builder check his specific data files and include them in the final quality check report.

Test data archive building, storage and upload:

The login page allows authenticating the user by communicating with the CTS to check password and authorizations. From the login page it is possible to set the properties for using the Test Data Builder. The properties file is automatically generated by the application if not present and can also be edited by hand.

The Test Data Builder main page allows filling metadata information required for a complete description of the test run. This page also presents the list of log files currently added and allows the user to check the quality of these files, either for one specific file, or for the complete archive at once.

The add file page is used to add log files and fill required information to describe the log recording context and conditions, along with any comment useful for log analysis. A quality check button allows the user to verify that the log is compliant with expected quality requirements.

Once ready, the user can generate the test data archive, which is stored locally. Then it is possible to upload it with one click to the CTS. The description file is automatically generated and DQCT is called by the Test Data Builder, therefore, a report on data quality is joined to the archive. The upload is done using HTTPS.

Test data archive reading, validating and upload:

Test Data Builder can also be used to only upload to the CTS existing test data archives from local storage. These archives can have been created by the application, or with other means. In this case, the Test Data Builder first checks the archives. Only well-formed archives, compliant with requirements and with correct description are accepted and uploaded.

2.5. Final KPI Specification

D2.5 [5] presented an initial set of KPIs, later updated in D5.1 [7]. As the project progressed towards the actual deployment of the corresponding tools, it became apparent that certain KPI definitions required revision and in some cases the introduction of more detailed KPI definitions. For instance, the definition of TE-KPI1.3-End to End Latency in D2.5 [5] discusses the option for per network segment measurements, however the KPI title and primary definition, which both focus on the E2E aspect, may be misleading. To clarify this the overall list of KPIs is revised as shown in Table 6. Any updates, compared to D2.5 and/or D5.1 are highlighted with *underlined and italics font,* and will be officially reported in the next WP5 deliverable i.e., D5.2. We use strikethrough font for KPIs dropped and explain in line the reasons for dropping them.

Table 6: Final KPI specification

KPI	Description
TE – KPI 1.1 User experienced data rate	Data rate as perceived at the application layer. It corresponds to the amount of application data (bits) correctly received within a certain time window (also known as *goodput*).
TE – KPI 1.2 Throughput	The instantaneous data rate / throughput as perceived at the network layer between two selected end-points. The end-points may belong to any segment of the overall network topology. It corresponds to the amount of data (bits) received per time unit.
TE – KPI 1.3 End to End 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 – KPI 1.3b 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. **Note:** this KPI is introduced only to provide support for other, non-application layer measurements of delay, since the original definition and title (End-to-end) point specifically to application layer measurements
TE – KPI 1.4 Control plane Latency	Control plane latency refers to the time to move from a battery efficient state (e.g., IDLE) to start of continuous data transfer (e.g., ACTIVE). This is a KPI aimed to shed further light on the end-to-end latency components i.e., identify the contribution of control plane processes to the overall perceived latency.

TE – KPI 1.5 User plane Latency	Contribution of the radio network to the time from when the source sends a packet to when the destination receives it. It is defined as the 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.
<u>TE – KPI 1.6</u> <u>Reliability</u>	Amount of application layer messages or <u>network layer packets (subject to measurement level i.e., L2 or L1)</u> 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 – KPI 1.7 Position accuracy	Deviation between RTK-GPS location information and the measured position of a UE via 5G positioning services. Applies only to the NL trial site.
TE – KPI 1.8 Network Capacity	Maximum data volume transferred (downlink and/or uplink) per time interval over a dedicated area.
~~TE – KPI 1.9~~ ~~Mean Time to Repair (MTTR)~~	~~Statistic mean downtime before the system/component is in operations again. The MTTR here refers to failing software components e.g., a virtual network function (VNF).~~ ***Removal reason:*** *This KPI is removed from our list since no particular solution aims to investigate related failsafe/recovery/failover operations.*
TE – KPI 2.1 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	Applies to scenarios where an active application-level session (e.g., communication between application client at UE/OBU and the Application Server) needs to be transferred from a source to a destination application instance (e.g., located at MEC hosts at the source and destination networks respectively) as a result of a cross-border mobility event. The KPI describes the 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	The 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 <u>*time difference between RRC Connection Reconfiguration and New Data Receive messages.*</u>

~~TE-KPI2.4-International Roaming Latency~~	~~Applies to scenarios of cross-border mobility, where mobile UEs cross the physical borders between the involved countries, eventually triggering a roaming event. The KPI describes the duration of the roaming procedure, from initiation till completion and eventual continuation of communication sessions.~~ ***Removal reason:*** *This KPI is removed from our list since the corresponding latency will be actually equal to TE-KPI2.3-Mobility interruption time.*
~~TE-KPI2.5-National Roaming Latency~~	~~Applies to inter-PLMN handover scenarios, where the involved networks operate within the national boarders i.e., alternative operators. This KPI applies to the case of the NL trial site, where such a trial setup will be available. On a technical front, this KPI is equivalent to TE-KPI2.3.~~ ***Removal reason:*** *This KPI is removed from our list since the corresponding latency will be actually equal to TE-KPI2.3-Mobility interruption time.*

2.6. Targeted Cross-Border Issues Analysis

The work of 5G-MOBIX is focused on identifying the key challenges in attempting to provide seamless connectivity to CAM enabled vehicles when crossing national borders and hence performing an inter-PLMN HO, resulting into roaming in the visited PLMN, and to test and evaluate the effectiveness of various features, configurations and solutions in addressing the respective challenges. In this section the technical challenges in scope of the 5G-MOBIX work and their respective solutions will be discussed, while the non-technical aspects of inter-PLMN mobility are discussed in the WP6 deliverables and the 5G-MOBIX Deployment Study [8] [9].

As a first step, the 5G-MOBIX 5G network experts have identified the key challenges or **Cross-Border Issues (XBIs)** that contribute to service interruption and/or performance degradation (in terms of latency, reliability, throughput, etc.) when a CAM enabled vehicle is crossing national borders and consequently changing its serving PLMN. During this process, the vehicle is performing an inter-PLMN Handover (HO), leaving its home network (PLMN) and ending up roaming in the visiting PLMN. The identification, performance degradation measurement and impact analysis of each of these XBIs, has been the key focus of all the 5G-MOBIX cross-border corridors (CBCs) and national trial Sites (TSs).

As a second step, the most promising 5G features, technologies and configurations/settings that could mitigate or even completely counteract the effects of each of these XBIs, were identified by the 5G-MOBIX experts and listed under the common name **Considered Solutions (CSs)**. Each CS constitutes a potential solution that could be implemented on the network, vehicle/OBU or application level and has a significant chance of improving the experienced connectivity performance when performing an inter-PLMN HO. Specific XBI-CS pairs are defined and trialled at each of the CBCs/TSs in order to provide insights on *i)* the impact of a certain XBI on the experienced performance of each of the selected CAM use cases and ii) the degree to which each of the progressed CSs mitigate the impact of the respective XBI and delivers the best possible performance during border-crossing.

The entire trialling effort of 5G-MOBIX across all CBCs/TSs has been focused on the evaluation of the above XBI-CS pairs in order to provide insights into the best possible technologies and 5G network configurations that will allow for an optimized border-crossing experience for 5G enabled CAM vehicles/services. Table 7 and Table 8 below provide the definitions of the 5G-MOBIX Cross-Border Issues (XBIs) and Considered Solutions (CSs), as used by all 5G-MOBIX CBCs/TSs for their trials. Table 7 includes the Associated CSs in order to provide quick insights into which considered solutions apply to a specific XBI, while Table 8 includes the Related CSs column in order to indicate which are the other relevant solutions that could be compared in terms of performance, in order to decide which is the best/most suitable solution for a specific XBI.

Table 7: 5G-MOBIX Cross-Border Issues (XBIs) definitions

XBI ID	Category	Title	Definition	Associated CSs
XBI_0	Telecom	*Baseline*	*Used to denote that the corresponding Test Case serves the role of the baseline, where no X-Border functionality (and testing) is considered*	*CS_0*
XBI_1	Telecom	NSA Roaming interruption	With current networks we see that when a UE crosses a border it tries to keep the connection to the previous network. This can result in a connection loss of several minutes. A new connection needs to be established and also a new data session needs to be set up. This behaviour is even worsened because of steering of roaming that is implemented by MNO's, trying to steer the UE to a preferred network and by doing so deny certain roaming requests.	CS_1 CS_2 CS_3
XBI_2	Telecom	SA Roaming interruption	Currently Roaming for SA networks has only been defined for basic roaming. No handover is specified and also the equivalent of the S10 interface for ePC (N14) has not been referenced as a roaming interface. Because of these limitations it is expected that the same issues will arise as seen in current networks leading to disconnect times of minutes.	CS_6 CS_13
XBI_3	Telecom	Inter-PLMN interconnection latency	Currently operators interconnect using a GRX network used for both signaling and user plane data. This network extends over multiple countries and operators and is typically designed for high continuity and throughput, this at the expense of low latency. Moreover, GRX connectivity may redirect traffic through far-away nodes (based on the GRX operator architecture) further increasing E2E latency, which is unsuitable for CAM applications.	CS_7 CS_8
XBI_4	Telecom	Low coverage Areas	Looking at current border areas we see very low coverage areas because of sparse populations at the border. In addition, given the current regulations, operators must take into account the max fieldstrengths	CS_4 CS_9 CS_10

			allowed at the border. On both sides of the borders the same frequencies are in use. Operators need to try and limit the interference. In addition border areas are often sparsely populated, giving little incentives to provide for increased capacity or coverage in those areas. As a result, areas of low or no coverage may appear close to the border. threatening the CAM aplication continuity.	
XBI_5	Telecom & Application	Session & Service Continuity	When directing the UE to a new datanetwork 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.	CS_4 CS_5 CS_6 CS_11 CS_12 CS_13 CS_14 CS_15 CS_16 CS_17 CS_18 CS_19 CS_20
XBI_6	Telecom	Data routing	When roaming normally the data traffic will be routed to the home network and connect to the data-network at the home PLMN. Crossing the border from home-PLMN to a visited-PLMN will then lead to higher latencies. As an alternative it is also possible that the UE uses a Local BreakOut (LBO) roaming, connecting to the closest edge which will result in a lower latency. However setting up a connection to a new data network will take time which might result to a connection interruption and the potential loss of data. Also finding the closest edge might take time if a query is needed by the UE to discover the closest edge after the switch to the plmn.	CS_16 CS_17 CS_18 CS_19
XBI_7	Telecom & Application	Insufficient Accuracy of GPS Positioning	Global Navigation Satellite Systems (GNSS) positioning cannot meet the stringent CAM requirements i.e., down to 20-30 cm accuracy, cannot be used while indoors (for example in tunnels, indoor parking/garages or lower decks of multi-level bridges) and have strong limitations in dense urban environments. GNSS also lacks a refresh	CS_20

			rate high enough to be used in safety critical applications. Without accurate geo-positioning, CAM applications that require external information based on absolute position cannot merge this information onto local maps with relative positions (distance to other vehicles/obstacles, lane position, etc.).	
XBI_8	Application	Dynamic QoS Continuity	A sudden drop in the network connection quality, in terms of bandwidth and latency, may happen when the vehicles move from one MNO to the other in a cross-border area as they usually mean distant areas to the base station of different MNOs, and fading antenna coverage to avoid overlaps. Specifically in roaming situations when the sessions and applications are resumed, a conservative approach could be more reliable as an eager communications rate can lead to performance degradation at the application level, in terms of steady framerate, high fidelity and continuous QoS, hindering the full potential of CAM solutions.	CS_21 CS_22 CS_26
XBI_9	Application	Geo-Constrained Information Dissemination	A connected vehicle usually needs to receive traffic information directly related to its surroundings, not the whole flow of CAM messages exchanged through the edge computing node it is connected to. When it is travelling close to the border, it might also want to receive some data from neighbouring geographical areas covered by a MEC node located in another PLMN. Also in this situation, not all CAM information exchanged through the neighbouring MEC is of interest to that specific connected vehicle. For instance, in the platooning application, the connected and autonomous members of the platoon solely need to exchange data with the platooning vehicles and possibly with some other vehicles and sensors in the vicinity. As a result, a geo-constrained information dissemination scheme should be devised in order to disseminate the relevant CAM data to the appropriate vehicles, in cross-border areas.	CS_23 CS_24 CS_25
XBI_10	Telecom	mmWave applicability	Not an X-border Issue per se, but the applicability in the CAM domain is of interest.	CS_25
XBI_11	Telecom	Network slicing applicability	Not an X-border Issue per se, but the applicability in the CAM domain is of interest.	CS_26

Table 8: Definitions of 5G-MOBIX Considered Solutions (CSs) for XBIs

CS ID	Title	Definition	Related CSs
CS_0	Feature OFF	*Used to denote that the corresponding Test Case serves the role of the baseline, where a specific CS is not active. When combined with an XBI other than XBI_0 it indicates the XBI for which it is considered as a baseline*	
CS_1	S1 handover with S10 interface using an NSA network	An S1 handover is a normal handover procedure also used within one PLMN when there is no X2 interface between the involved gNBs. It can furthermore happen that it also includes a change of MME, in which case the S10 interface is also used. An Inter-PLMN handover always goes along with a change of MMEs. Same information as for an X2 handover is exchanged between source and target gNB but the MMEs are relaying it. The source gNB asks the target gNB to accept the UE and the target gNB provides its configuration information. This information is provided to the UE so it can adapt, if needed, to the target gNB settings and quickly connect to it. Nevertheless, it has to detach from the source gNB and then synchronize with the target one where it then performs the random access procedure. Once this is done communication is resumed as the source gNB transferred all RAN context information to the target one. Furthermore, the S10 interface was used to conduct the core context transfer and routes are adapted towards the now serving target gNB and eventually gNB after the 5G leg was added and the path was switched.	CS_ 2 CS_3 CS_6 CS_7
CS_2	Release and redirect using an NSA network	Release with Redirect is s a procedure where the UE needs to re-attach and re-authenticate to the new network. No context information is transferred between gNBs or core networks regarding the current session. It therefore results in a service interruption as the UE attaches to the target gNB, has to authenticate and setup a new bearer session. The gNB will redirect the UE to the target network at the appropriate signal levels. The new network needs to be in the ePLMN list send previously.	CS_1 CS_3 CS_4 CS_5 CS_6 CS_7
CS_3	Release and redirect with S10 interface using an NSA network	Release with Redirect describes a procedure that is normally related to idle mode mobility, as it does not transfer context information between the source and target gNB. It therefore results in a service interruption as the UE attaches to the target gNB in idle mode and has then to transition to connected mode. In the core network, context information is exchanged between the source and destination core through the S10 interface. The UE does therefore not have to initiate the procedure to establish a packet data network connection as the session is resumed.	CS_1 CS_2 CS_4 CS_5 CS_6 CS_7
CS_4	Multi-modem / multi-SIM connectivity - Passive Mode	Multi-SIM approach can address service continuity challenges for V2N connectivity in any geographical location where connectivity to two (or more) PLMNs is possible using a device containing a SIM (physical or embedded) associated with each PLMN. This location could be within national borders with coverage from multiple PLMNs of same country,	CS_1 CS_2 CS_3 CS_5

		or at cross-border areas where there is overlap of coverage from PLMNs of neighbouring countries. The multi-SIM solution could provide redundancy and/or minimise interruption time when moving between PLMNs with overlapping coverage areas. This is possible through multi-SIM device selecting the 'best or high priority' connection or link (passive mode).	
CS_5	Multi-modem / multi-SIM connectivity- Link Aggregation	Multi-SIM approach can address service continuity challenges for V2N connectivity in any geographical location where connectivity to two (or more) PLMNs is possible using a device containing a SIM (physical or embedded) associated with each PLMN. This location could be within national borders with coverage from multiple PLMNs of same country, or at cross-border areas where there is overlap of coverage from PLMNs of neighbouring countries. The multi-SIM solution could provide redundancy and/or minimise interruption time when moving between PLMNs with overlapping coverage areas. This is possible through multi-SIM device utilising multiple connections in the same session (link aggregation or link bonding).	CS_1 CS_2 CS_3 CS_4
CS_6	Release and redirect using an SA network	Release with Redirect is s a procedure where the UE needs to re-attach and re-authenticate to the new network. No context information is transferred between gNBs or core networks regarding the current session. It therefore results in a service interruption as the UE attaches to the target gNB, has to authenticate and setup a new bearer session. The gNB will redirect the UE to the target network at the appropriate signal levels. The new network needs to be in the ePLMN list send previously.	CS_1 CS_2 CS_3 CS_7
CS_7	Internet-based Interconnection	Internet-based (e.g., IPX) interconnection is the main solution followed by MNOs for roaming purposes. Efficient service guarantee can be offered by complying with service level agreements (SLAs). The Internet-based interconnection links between two MNOs do not necessarily follow the optimum routing path in terms of number of hops, since the traffic may reach its destination MNO via far-away nodes, affecting thus the interconnection latency.	CS_8
CS_8	Direct Interconnection	Direct interconnection (via leased lines) is one solution that can be followed by MNOs for roaming purposes, especially for services that require low latency, such as CAM ones. The direct interconnection can secure the number of hops between two interconnected parties leading to low interconnection latency in a secure way and to better treatment of traffic management.	CS_7
CS_9	Satellite connectivity	Being able to provide continuous service and assist automated vehicles is challenging especially in rural or remote areas, including cross-border corridors, that are often left uncovered or late to be covered by terrestrial networks. In such coverage gap situations, NTN (non-terrestrial network) can be an attractive solution to ensure ubiquitous service offering thanks to its universal coverage. Different approaches can be used to decide when a vehicle should switch to NTN network. One of such solutions can be Predictive QoS.	CS_0

CS_10	MEC service discovery and migration using enhanced DNS support	A vehicle's trajectory on the road/highway may cross the serving areas of different cross MEC systems of different PLMNs both within nation's border and at cross-border areas. Consequently, service continuity between the vehicle and the distributed MEC system(s) needs to be maintained in such operational conditions (ref. ETSI GS MEC 030, 5GAA white paper #32). The implemented 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 (DNS-based solutions are surveyed in ETSI ISG MEC white paper[3])	CS_11 CS_12
CS_11	Imminent HO detection & Proactive IP change alert	This is an application-level solution, during which an edge-based application server continuously compares the GPS coordinates of the OBU, and issues an "imminent HO detection" alert once it is determined that the OBU has a trajectory towards national borders, and an imminent HO to a neighbouring network is expected. Once this alert is triggered, the server may proactively notify the OBU that it will soon receive a new IP (once it crosses the border) address from a designated IP pool of the neighbouring network (if known) and also communicate the IP address of the neighbouring edge node hosting the application instance in the neighbouring country. This is the new IP address that the OBU should transmit its data after the HO. This mechanism should enhance service level continuity, as the OBU will be pro-actively notified regarding its own IP and the edge servers IP, eliminating any search period in the neighbouring network.	CS_0 CS_10 CS_12
CS_12	Inter-PLMN HO, AF make-before-break, SA	To allow for the transition between different edges without the application disconnecting a scheme is proposed where the application receives a notification from the application function when a new edge is to be used. The UE will need to set up an extra PDN session allowing to connect to the new edge and the application at the vehicle will need to reconnect to the application running at the new edge. After this is completed the old PDN session to the previous edge can be closed. The application functions is running near the 5G Core having a connection with the NEF to receive location updates of the UE.	CS_10 CS_11
CS_13	Double MQTT client	This solution aims to address the session and service continuity challenge and in particular the service disruption expected due to the interruption time inquired by the MQTT client-server session establishment/tear down procedures i.e., upon a handover event an MQTT client is typically required to gracefully tear down its session with the MQTT server at the home PLMN and then establish a new one with the MQTT server at the visiting network. The signalling process is time consuming resulting in service disruption. The double MQTT client solution employs two client instances e.g., A and B, with A being connected to the home PLMN server. Upon HO, client B initiates the	*CS_0*

[3] https://www.etsi.org/images/files/ETSIWhitePapers/etsi-wp39-Enhanced-DNS-Support-towards-Distributed-MEC-Environment.pdf

		session establishment procedure with the visited PLMN server, while A is in the process of tearing down the original session.	
CS_14	Inter-MEC exchange of data	In order to address service continuity challenges when the service requiring a low latency connection with a MQTT server is upon a handover event, two instances of the server MQTT are created and deployed at the MEC of the home and the visited PLMNs. The home MQTT is directly publishing the messages in the visited one (and vice versa), managing both MQTTs the same information in every moment avoiding its segmentation in two MQTT servers upon the HO event.	CS_15
CS_15	Inter-server exchange of data	In order to address service continuity challenges when the service requiring a high throughput (but not very strict latency requirements) is upon a handover event, two instances of the same application are created and deployed in a server behind the MEC (connected via high speed fibre) of the home and the visited PLMNs. Hosting the application in a server, instead of the MEC, the MEC saturation is avoided and gives the service provider direct control over its application. Duplicating the server applications, the different regulatory issues in both PLMNs can be managed if needed and the latency is also minimized.	CS_14
CS_16	LBO NSA	In local breakout for NSA 5G networks, the user plane (UP) traffic of a roaming UE is served directly by the V-PLMN, while authentication and handling of subscription data is managed by the H-PLMN. Specifically, only signalling data is routed to the H-PLMN, which allows more efficient routing in terms of latency, whereas the IP address of a roaming user is obtained from the V-PLMN.	CS_17
CS_17	HR NSA	In home routed for NSA 5G networks, the H-PLMN provides the IP address for the roaming users. The user plane (UP) traffic of the roaming UE is always served by H-PLMN, thus giving more control over the users' traffic. The MME in the V-PLMN contacts the HSS in the subscribers' H-PLMN to obtain subscriber data. When the subscriber is accepted by the V-PLMN, the user plane to the packet data gateway (PGW) is established in the H-PLMN where the subscriber's IP address is anchored. The main drawback of this model is the high latency incurred, since UP traffic must be tunnelled towards the H-PLMN.	CS_16
CS_18	LBO SA	With local breakout for SA 5G networks the UE sets up a PDU session with a UPF in the visited network. This in contrast to Home routed (the current default) where data is routed back to the home network. To setup a LBO PDU session the SMF in the visited network needs to contact the UDM in the home network over the N10 interface. All the other roaming interfaces (N8, N12, N21, N24, N27, N31 and N32) are also needed, with an exception of the N9 and N16 interface since the data stays local.	CS_19
CS_19	HR SA	Using home routed roaming the data is routed back to the data network at the home PLMN. The data is routed from the UE to the UPF of the V-PLMN and from there to the UPF of the H-PLMN over the N9 interface. While the latency of a home routed session will most likely increase significantly this is probably the only data session that can	CS_18

		continue to exist when a handover takes place from the H-PLMN to the V-PLMN. It is however possible to have multiple sessions in parallel so next to a home routed session also a local breakout session can be set up to a local data network.	
CS_20	Compressed sensing positioning	Augmenting positioning through the use of compressed sensing techniques on the OFDM signal (improves localization accuracy where only few reference base stations are available), taking advantage of angular information for angle of arrival/departure and sparsity of mmWave channels.	*CS_0*
CS_21	Adaptive Video Streaming	Adaptive QoS bitrate and framerate. Depending on different thresholds mapping good and poor network performance for the intended application demand, the bitrate and the framerate are set to the nominal values (high fidelity) or downgraded to ensure that a suitable representation is sent in any situation guaranteeing a functional operation of the CAM application. The conservative approach starting with a low fidelity and upgrading to high when possible, makes application resume faster and more reliable.	*CS_0*
CS_22	Predictive QoS	Predictive QoS is a solution that adapts application data rates based on predicted communication quality. Quality prediction is based on machine learning algorithms that trained using various information including quality, bandwidth, spectrum, cell occupation, uplink and downlink data rates, delay, user's position, speed, orientation collected from the cellular network, applications, and users. The predicted quality is then communicated to users/applications via so-called In-Advance QoS Notification (IQN), in which the QoS prediction module suggests vehicles to adapt its e.g., video data rate to a given value etc. Upon reception of an IQN, the user/application adapts its data rate accordingly avoiding unnecessary packet loss and throughput degradation.	*CS_0*
CS_23	Uu geobroadcast	The information of standard ETSI C-ITS messages is disseminated via Uu interface. Using a MQTT broker and publisher/subscriber architecture, the broker filters the information and forwards to the vehicles only messages from the infrastructure that are relevant for their driving direction and their current location/area. Brokers in contiguous areas, for example in a cross-border scenario, exchange the information produced in their areas. Therefore, a broker can forward relevant information from other broker to a vehicle in its area if the conditions are the right ones (e.g., a vehicle driving towards the border will receive information from the other side of the border.)	CS_14
CS_24	PC5 geobroacast	Use of PC5 interface holding geo-localized characteristics by design. The RSUs broadcast infrastructure information (ITS messages) which is received only by the UEs in that PC5 coverage area, without the need of an MQTT broker. This solution is also used in specific use cases only requiring short-range communications, e.g., platooning. In a cross-border scenario, the information is received independently of the actual border side or registered MNO. If the UE is in PC5 coverage area, it will receive the information.	CS_23

CS_25	mmWave 5G	mmWave bands (24.25GHz-52.6GHz), which can provide as high as 10 Gbps data rate, can be attractive for CAM services. particularly those needing exchange of large volume data (e.g., collective perception). It is most likely that mmWave spectrum bands are/will be attributed to verticals allowing different actors (e.g., a road operator) install 5G networks. mmWave 5G network can hence provide improved quality and service continuity in high dense or low network coverage areas (including at the cross borders).	*CS_0*
CS_26	Network slicing	Partitioning of data and services in different slices to guarantee service performance in one network AND/OR across networks when roaming. Network slicing has been specified in 3GPP in various normative documents both on the requirement level (TS 22.261) [10], on the architecture level (TS 23.501) [11], procedure level (TS23.502) [12] and at the management level (TS 28.530) [13]. The 5G-Mobix use of slicing technology follows these and other 3GPP standards. Two slices are created, one slice for regular EMBB data and one slice for remote driving service, including uplink video and control data. Priority mechanisms should then prevent the disturbance of remote driving data because of generated load in the regular EMBB slice.	*CS_0*

As mentioned above, all trials executed at the CBCs/TSs of 5G-MOBIX are related to the evaluation of the impact of the defined XBIs and the degree to which performance is improved by the application of one of the mentioned CSs. The fact that all the XBIs and CSs are trialled in more than one CBC/TS adds a lot of value to the analysis performed by 5G-MOBIX, as the trial results at the different CBCs/TSs will complement each other and will provide broader insights into which solutions has the largest potential and under what conditions (e.g., two different CBCs/TSs may be evaluating the impact of the same XBI while using different solutions to mitigate its effects).

To provide an overview of the work performed in each CBC/TS of 5G-MOBIX and to highlight the importance of the extensive trials taking place across the 5G-MOBIX sites and the complementarity of solutions, Figure 4 and Figure 5 provide the overview of XBIs/CSs addressed in each site and the number of CBC/TSs that address each XBI, respectively.

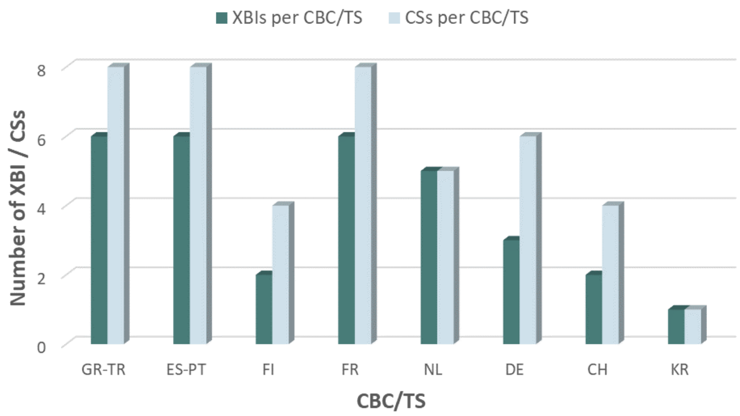


Figure 4: Overview of number of XBIs and CSs addressed in each 5G-MOBIX CBC/TS

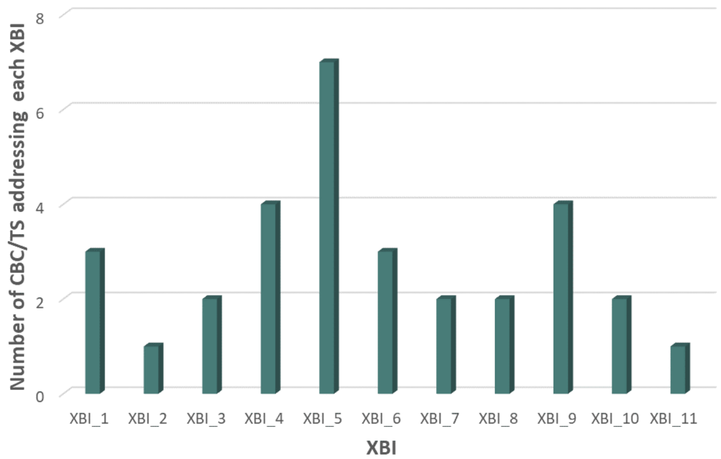


Figure 5: Overview of number of CBCs/TS addressing each XBI

It can be seen that the two cross border corridors indeed address the larger number of XBIs and CSs (as expected), while the TS are providing critical contribution by i) assessing XBIs and/or solutions that were note able to be assessed in the CBCs (due to restrictions of trialling in a real highway with real traffic) and ii) providing complementary data on XBIs and CSs trialled at both the CBCs and the TSs.

As this work is the core focus of the project's evaluation framework, all relevant results and detailed analysis and UC validations regarding the impact of the XBIs and the effectiveness of the considered solutions, will be presented in the deliverables of the Evaluation work package (WP5). Some, 5G network measurements (and their analysis), not targeted specifically at an XBI, but rather to validate the proper deployment of the 5G networks and their readiness to support the trials are provided in this deliverable in annex sections.

2.7. Deployment Timeline

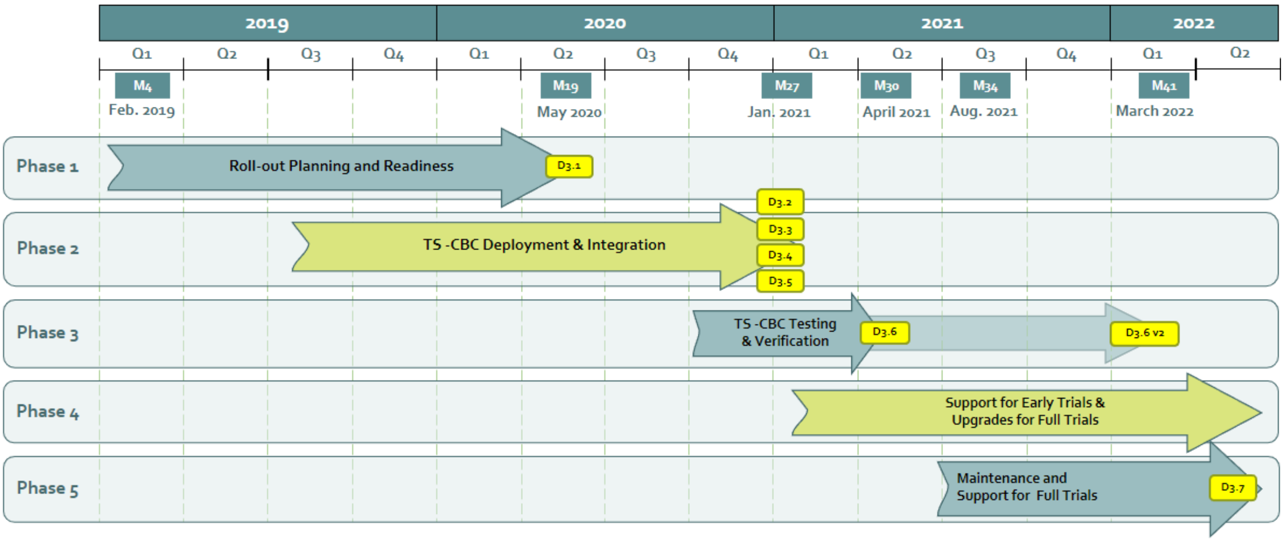


Figure 6: 5G-MOBIX Deployment Timeline

5G-MOBIX WP3, deployment, integration, and roll-out activities have been carried out based on the schedule depicted in Figure 6 with some minor delays and extensions. In addition to travel restriction requirements that prevented the travel of research personnel to the actual test sites, there have also been problems regarding providing test vehicles to cross borders. Cooperation with local partners was emphasized to mitigate the impact of the travel restrictions on the deployment activities, and remote support was provided in the necessary cases. Ongoing pandemic restrictions mainly affected the CBCs due to the necessity of collaboration from multiple project participants. Therefore phase 3 was extended until the end of the 2nd quarter of 2021 to ease the testing and verification procedures. Furthermore, phase 4 regarding support & upgrades for the trials has also been extended until the project submission date, the second quarter of 2022.

2.8. 5G Network Insights – Common Set of KPIs

This section presents the measurements taken by all 5G-MOBIX networks that were deployed at each CBC/TS, in an attempt to provide some insights regarding the relevant performance of all the deployed 5G networks. It can be understood that these numbers cannot be used for a straightforward comparison of performance among the different networks, as they operate under completely different conditions (terrain, distance to gNBs, antenna settings and tilts, weather conditions, etc.), however they provide valuable insights into the achieved performance at each deployed testbed/network. The 5G-MOBIX partners agreed on a minimum common set of KPIs to be measured at each testbed/network under as much as possible identical conditions, in order to facilitate this exercise. The following sub-sections provide the measurements taken at each CBC/TS while Section 2.8.8 provides the summary and gained insights from the cross-comparison of these measurements.

2.8.1. ES-PT Network KPIs

The following tables summarize and compare the network parameters (RSRP and SINR) for all the involved antennas. The values are calculated in average for every antenna in every different case by CTAG. The average value in dB and dBm is calculated using the arithmetic average.

Table 9: ES-PT KPIs RSRP and SINR values

TC ID	Test Case (TC) Name	UL / DL	TCP / UDP	A-55		CTAG's test tracks		Old Bridge ES		New Bridge ES		Old Bridge PT		New Bridge PT		SA / NSA
				RSRP (dBm)	SINR (dB)	RSRP (dBm)	SINR (dB)	RSRP (dBm)	SINR (dB)	RSRP (dBm)	SINR (dB)	RSRP (dBm)	SINR (dB)	RSRP (dBm)	SINR (dB)	
KPI_AG1	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP & UDP	LTE: -69 NR: -86	LTE: 18.5 NR: 25	LTE: -60.5 NR: -52	LTE: 22 NR: 36.5	LTE: -72 NR: -83.5	LTE: 19 NR: 29.5	LTE: -70 NR: -82	LTE: 18.5 NR: 25	LTE: -60 NR: -67	LTE: 21 NR: 20.5	LTE: -65 NR: -66	LTE: 23 NR: 31	NSA
KPI_AG2		**UL**	TCP & UDP	LTE: -69 NR: -86	LTE: 18.5 NR: 25	LTE: -60.5 NR: -52	LTE: 22 NR: 36.5	LTE: -72 NR: -83.5	LTE: 19 NR: 29.5	LTE: -70 NR: -82	LTE: 18.5 NR: 25	LTE: -60 NR: -67	LTE: 21 NR: 20.5	LTE: -65 NR: -66	LTE: 23 NR: 31	NSA

KPI_ AG3	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP & UDP	LTE: -87 NR: -105.5	LTE: 13 NR: 18.5	LTE: -98.5 NR: -95.5	LTE: 9.5 NR: 13.5	LTE: -99.5 NR: -111	LTE: 9.5 NR: 11	LTE: -98 NR: -105.5	LTE: 15.5 NR: 66	LTE: -109.5 NR: -115	LTE: 5.5 NR: 9	LTE: -94.5 NR: -81.5	LTE: 14 NR: 41	NSA
KPI_ AG4		**UL**	TCP & UDP	LTE: -87 NR: -105.5	LTE: 13 NR: 18.5	LTE: -98.5 NR: -95.5	LTE: 9.5 NR: 13.5	LTE: -99.5 NR: -111	LTE: 9.5 NR: 11	LTE: -98 NR: -105.5	LTE: 15.5 NR: 66	LTE: -109.5 NR: -115	LTE: 5.5 NR: 9	LTE: -94.5 NR: -81.5	LTE: 14 NR: 41	NSA
KPI_ AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	LTE: -97.5 NR: -102	LTE: 12.5 NR: 16.5	LTE: -84 NR: -80.5	LTE: 14.5 NR: 23.5	LTE: -89.5 NR: -99	LTE: 14 NR: 18	LTE: -90 NR: -98.5	LTE: 15.5 NR: 14	LTE: -84.5 NR: -92.5	LTE: 16 NR: 19.5	LTE: -77 NR: -71.5	LTE: 19 NR: 25.5	NSA
KPI_ AG6		**UL**	TCP	LTE: -97.5 NR: -102	LTE: 12.5 NR: 16.5	LTE: -84 NR: -80.5	LTE: 14.5 NR: 23.5	LTE: -89.5 NR: -99	LTE: 14 NR: 18	LTE: -90 NR: -98.5	LTE: 15.5 NR: 14	LTE: -84.5 NR: -92.5	LTE: 16 NR: 19.5	LTE: -77 NR: -71.5	LTE: 19 NR: 25.5	NSA
KPI_ AG7	**User Plane Latency (e2e)**	**DL**	PING	LTE: -87 NR: -105.5	LTE: 13 NR: 18.5	LTE: -62 NR: -68	LTE: 30 NR: 23	LTE: -70.5 NR: -80.5	LTE: 17 NR: 23	LTE: -71.5 NR: -84	LTE: 17 NR: 58	LTE: -62 NR: -68	LTE: 18 NR: 20.5	LTE: -70 NR: -73.5	LTE: 23.5 NR: 32.5	NSA
KPI_ AG8	**UL Packet Loss Rate (%) - mobile**	**UL**	UDP	LTE: -88 NR: -60.5	LTE: 12.5 NR: 18	LTE: -80 NR: -79.5	LTE: -14.5 NR: -23.5	LTE: -86.5 NR: -59	LTE: 11.5 NR: 20.5	LTE: -86 NR: -98.5	LTE: 16.5 NR: 15	LTE: -77.5 NR: -79.5	LTE: 19 NR: 19	LTE: -75.5 NR: -70.5	LTE: 19.5 NR: 33	NSA
KPI_ AG9	**DL Packet Loss Rate (%) - mobile**	**DL**	UDP	LTE: -88 NR: -60.5	LTE: 12.5 NR: 18	LTE: -80 NR: -79.5	LTE: 14.5 NR: 23.5	LTE: -86.5 NR: -59	LTE: 11.5 NR: 20.5	LTE: -86 NR: -98.5	LTE: 16.5 NR: 15	LTE: -77.5 NR: -79.5	LTE: 19 NR: 19	LTE: -75.5 NR: -70.5	LTE: 19.5 NR: 33	NSA

Table 10: ES-PT KPIs A28 RSRP and SINR values

TC ID	Test Case (TC) Name	UL / DL	TCP / UDP	A28		Type
				RSRP (dBm)	SINR(dB)	
KPI_AG1	**DL Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP & UDP	LTE: -68 NR: -85.6	LTE: 12.5 NR: 29	NSA
KPI_AG2	**UL Data Throughput of Single User (Mbps) - stationary / Central**	**UL**	TCP & UDP	LTE: -67 NR: -86	LTE: 11.5 NR: 21	NSA
KPI_AG3	**DL Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP & UDP	LTE: -105.5 NR: -99.5	LTE: 12 NR: 17.5	NSA
KPI_AG4	**UL Data Throughput of Single User (Mbps) - stationary / Cell Edge**	**UL**	TCP & UDP	LTE: -106 NR: -100	LTE: 13 NR: 21.5	NSA
KPI_AG5	**DL Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	LTE: -80.5 NR: -91.5	LTE: 14.5 NR: 24	NSA
KPI_AG6	**UL Data Throughput of Single User (Mbps) - mobile**	**UL**	TCP	LTE: -93.5 NR: -92.5	LTE: 12.5 NR: 26	NSA
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING	LTE: -66 NR: -84	LTE: 10.5 NR: 23.5	NSA
KPI_AG8	**UL Packet Loss Rate (%) - mobile**	**UL**	UDP	LTE: -85 NR: -88	LTE: 10.5 NR: 27	NSA
KPI_AG9	**DL Packet Loss Rate (%) - mobile**	**DL**	UDP	LTE: -92.5 NR: -91	LTE: 9.5 NR: 25	NSA

The following tables (Table 11 to Table 17) summarize the mandatory KPIs for every TC carried out by CTAG. Each antenna was placed in a separated table. The way to generate the UDP values is explained in the appendix, 5G-MOBIX-D3.7-appendices-v0.2-ES-PT_CTAG.docx but as a summary, the injected traffic is 120% of the average value obtained in the TCP case. For some of the UDP cases, due to loss of connectivity at high data rates, it was necessary to reduce the data rate until a value with a stable enough connectivity. The cases in which this limitation occurs are duly indicated in the appendix.

A-55

Table 11: ES-PT KPIs A-55 RSRP and SINR values

TC ID	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP	344.32	424.31	283.27	380.00	8.61	NSA	Telefónica
KPI_AG1			UDP	415.97	449.71	407.23	421.55	10.40	NSA	Telefónica
KPI_AG2		**UL**	TCP	75.10	99.95	66.01	83.72	1.88	NSA	Telefónica
KPI_AG2			UDP	80.00	80.29	79.93	80.03	2.00	NSA	Nokia
KPI_AG3	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP	258.07	324.79	207.77	294.99	6.45	NSA	Telefónica
KPI_AG3			UDP	305.07	341.62	283.78	333.88	7.63	NSA	Telefónica
KPI_AG4		**UL**	TCP	40.49	63.42	33.49	47.29	1.20	NSA	Telefónica
KPI_AG4			UDP	23.02	46.19	45.97	46.08	1.15	NSA	Telefónica
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	273.37	457.22	70.16	393.06	7.34	NSA	Telefónica
KPI_AG6		**UL**	TCP	47.29	99.63	19.49	79.38	1.15	NSA	Telefónica
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING 32 bytes	18.87	214.33	11.20	23.81	N/A	NSA	Telefónica
KPI_AG7		**DL**	PING 1400 bytes	24.18	235.33	16.77	29.27	N/A	NSA	Telefónica
KPI_AG8	**Packet Loss Rate (%) - mobile**	**UL**	UDP	0.03	0.57	0.00	0.00	1.69	NSA	Telefónica
KPI_AG9		**DL**	UDP	24.73	100.0	0.00	94.01	7.85	NSA	Telefónica

CTAG's Test Tracks

Table 12: ES-PT CTAG Test Track KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	Data Throughput of Single User (Mbps) -Stationary / Central	DL	TCP	352.99	425.24	309.84	382.57	8.83	NSA	Telefónica
KPI_AG1			UDP	396.46	411.20	390.36	403.47	9.93	NSA	Telefónica
KPI_AG2		UL	TCP	61.44	84.015	56.75	176.52	1.55	NSA	Telefónica
KPI_AG2			UDP	74.78	75.25	74.91	75.02	1.88	NSA	Telefónica
KPI_AG3	Data Throughput of Single User (Mbps) - stationary/ Cell Edge	DL	TCP	162.55	250.45	145.20	176.52	4.03	NSA	Telefónica
KPI_AG3			UDP	169.47	188.13	156.49	179.73	4.22	NSA	Telefónica
KPI_AG4		UL	TCP	48.16	69.60	42.68	53.08	1.20	NSA	Telefónica
KPI_AG4			UDP	75.00	75.19	74.91	75.02	1.88	NSA	Telefónica
KPI_AG5	Data Throughput of Single User (Mbps) - mobile	DL	TCP	257.07	392.68	169.60	361.37	6.43	NSA	Telefónica
KPI_AG6		UL	TCP	55.18	84.00	46.11	64.84	1.38	NSA	Telefónica
KPI_AG7	User Plane Latency (e2e)	DL	PING 32 bytes	20.01	134	12.18	24.55	N/A	NSA	Telefónica
KPI_AG7		DL	PING 1400 bytes	25.36	134	17.05	33.30	N/A	NSA	Telefónica
KPI_AG8	Packet Loss Rate (%) - mobile	UL	UDP	6.58	79.03	0.00	15.48	10.93	NSA	Telefónica
KPI_AG9		DL	UDP	31.43	87.21	11.11	54.88	7.35	NSA	Telefónica

Old Bridge ES

Table 13: ES-PT CBC ES Old Bridge KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP	364.12	435.10	324.25	404.00	9.10	NSA	Telefónica
KPI_AG1			UDP	412.09	450.57	386.33	432.82	10.30	NSA	Telefónica
KPI_AG2		**UL**	TCP	62.83	88.92	53.07	75.29	1.57	NSA	Telefónica
KPI_AG2			UDP	75.50	75.97	75.43	75.57	1.89	NSA	Telefónica
KPI_AG3	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP	172.12	306.71	137.80	182.26	4.08	NSA	Telefónica
KPI_AG3			UDP	171.55	185.94	159.38	180.56	4.34	NSA	Telefónica
KPI_AG4		**UL**	TCP	15.12	25.01	9.49	16.42	0.34	NSA	Telefónica
KPI_AG4			UDP	16.00	16.16	15.98	16.09	0.40	NSA	Telefónica
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	220.47	358.51	131.09	317.39	5.51	NSA	Telefónica
KPI_AG6		**UL**	TCP	34.02	92.02	11.72	65.39	0.85	NSA	Telefónica
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING 32 bytes	16.69	156	11.32	27.50	N/A	NSA	Telefónica
KPI_AG7		**DL**	PING 1400 bytes	25.33	176.33	16.55	32.65	N/A	NSA	Telefónica
KPI_AG8	**Packet Loss Rate (%) - mobile**	**UL**	UDP	0.35	33.55	0.00	0.08	1.88	NSA	Telefónica
KPI_AG9		**DL**	UDP	35.21	91.82	1.86	69.16	7.03	NSA	Telefónica

New Bridge ES

Table 14: ES-PT CBC ES New Bridge KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	Data Throughput of Single User (Mbps) -Stationary / Central	DL	TCP	344.32	424.31	292.27	70.38	8.61	NSA	Telefónica
KPI_AG1			UDP	347.03	384.13	336.18	352.00	8.68	NSA	Telefónica
KPI_AG2		UL	TCP	77.05	96.39	71.43	85.18	1.94	NSA	Telefónica
KPI_AG2			UDP	31.06	93.64	92.98	93.09	2.33	NSA	Telefónica
KPI_AG3	Data Throughput of Single User (Mbps) - stationary/ Cell Edge	DL	TCP	205.95	287.67	180.11	238.04	5.08	NSA	Telefónica
KPI_AG3			UDP	206.99	245.61	188.94	227.94	5.18	NSA	Telefónica
KPI_AG4		UL	TCP	23.83	39.97	20.18	27.80	0.60	NSA	Telefónica
KPI_AG4			UDP	28.50	28.53	28.42	28.52	0.71	NSA	Telefónica
KPI_AG5	Data Throughput of Single User (Mbps) - mobile	DL	TCP	182.46	299.82	80.36	273.82	4.56	NSA	Telefónica
KPI_AG6		UL	TCP	36.20	73.62	6.41	59.08	0.91	NSA	Telefónica
KPI_AG7	User Plane Latency (e2e)	DL	PING 32bytes	19.46	167.00	10.91	27.23	N/A	NSA	Telefónica
KPI_AG7		DL	PING 1400 bytes	24.49	104.00	16.97	33.06	N/A	NSA	Telefónica
KPI_AG8	Packet Loss Rate (%) - mobile	UL	UDP	0.05	0.75	0.00	0.09	2.00	NSA	Telefónica
KPI_AG9		DL	UDP	24.89	77.42	0.00	65.67	6.55	NSA	Telefónica

Old Bridge PT

Table 15: ES-PT CBC PT Old Bridge KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP	477.27	544.68	432.11	519.80	11.93	NSA	NOOS
KPI_AG1			UDP	556.46	623.01	552.53	574.40	13.91	NSA	NOOS
KPI_AG2		**UL**	TCP	107.58	135.55	96.22	120.74	2.69	NSA	NOOS
KPI_AG2			UDP	110	110.01	109.91	110.02	2.75	NSA	NOOS
KPI_AG3	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP	69.37	120.91	53.57	84.46	1.73	NSA	NOOS
KPI_AG3			UDP	10.69	16.45	7.14	13.88	0.27	NSA	NOOS
KPI_AG4		**UL**	TCP	19.29	50.92	10.67	27.86	0.48	NSA	NOOS
KPI_AG4			UDP	23.00	23.13	22.98	23.09	0.58	NSA	NOOS
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	243.57	533.05	50.16	484.42	6.09	NSA	NOOS
KPI_AG6		**UL**	TCP	71.36	140.92	17.05	120.31	1.78	NSA	NOOS
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING 32 bytes	70.72	145.67	16.38	192.90	N/A	NSA	NOOS
KPI_AG7		**DL**	PING 1400bytes	51.63	163.67	27.20	89.52	N/A	NSA	NOOS
KPI_AG8	**Packet Loss Rate (%) - mobile**	**UL**	UDP	0.04	9.41	0.00	0.08	2.75	NSA	NOOS
KPI_AG9		**DL**	UDP	32.24	95.74	0.00	79.24	8.60	NSA	NOOS

New Bridge PT

Table 16: ES-PT CBC PT New Bridge KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	Data Throughput of Single User (Mbps) -Stationary / Central	DL	TCP	370.41	462.64	316.45	430.25	9.26	NSA	NOOS
KPI_AG1			UDP	371.19	523.83	204.31	456.37	9.28	NSA	NOOS
KPI_AG2		UL	TCP	103.92	149.34	90.92	115.74	2.60	NSA	NOOS
KPI_AG2			UDP	100	100.09	99.99	100.09	2.5	NSA	NOOS
KPI_AG3	Data Throughput of Single User (Mbps) - stationary/ Cell Edge	DL	TCP	156.68	232.75	101.59	192.49	3.91	NSA	NOOS
KPI_AG3			UDP	10.81	18.69	7.73	14.70	0.27	NSA	NOOS
KPI_AG4		UL	TCP	28.60	58.54	18.39	40.97	0.72	NSA	NOOS
KPI_AG4			UDP	34.00	34.07	33.96	34.06	0.85	NSA	NOOS
KPI_AG5	Data Throughput of Single User (Mbps) - mobile	DL	TCP	250.81	457.45	148.80	386.09	6.42	NSA	NOOS
KPI_AG6		UL	TCP	59.77	129.23	18.41	108.34	1.49	NSA	NOOS
KPI_AG7	User Plane Latency (e2e)	DL	PING 32 bytes	69.50	162.00	23.00	131.67	N/A	NSA	NOOS
KPI_AG7		DL	PING 1400 bytes	50.24	158.67	29.00	88.14	N/A	NSA	NOOS
KPI_AG8	Packet Loss Rate (%) - mobile	UL	UDP	0.01	0.08	0.00	0.02	2.5	NSA	NOOS
KPI_AG9		DL	UDP	8.40	54.21	0.00	22.18	8.95	NSA	NOOS

A28

Table 17: ES-PT CBC A28 KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP	313.93	337.88	180.88	287.58	5.83	NSA	NOOS
KPI_AG1			UDP	246.38	335.18	197.23	292.29	6.16	NSA	NOOS
KPI_AG2		**UL**	TCP	94.03	119.28	74.57	107.47	2.28	NSA	NOOS
KPI_AG2			UDP	80.00	80.04	79.93	80.04	2.0	NSA	NOOS
KPI_AG3	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP	197.02	305.23	126.34	264.41	4.93	NSA	NOOS
KPI_AG3			UDP	166.67	297.92	100.92	227.20	4.18	NSA	NOOS
KPI_AG4		**UL**	TCP	6.38	14.10	3.37	9.66	0.16	NSA	NOOS
KPI_AG4			UDP	7.60	7.63	7.52	7.63	0.19	NSA	NOOS
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	248.73	390.57	169.62	340.71	6.22	NSA	NOOS
KPI_AG6		**UL**	TCP	40.69	101.79	13.71	31.86	1.02	NSA	NOOS
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING 32 bytes	72.31	153.33	18.12	133.63	N/A	NSA	NOOS
KPI_AG7		**DL**	PING 1400 bytes	55.42	166	27	122.99	N/A	NSA	NOOS
KPI_AG8	**Packet Loss Rate (%) - mobile**	**UL**	UDP	0.06	0.03	0.00	0.05	1.5	NSA	NOOS
KPI_AG9		**DL**	UDP	9.41	65.98	0.00	27.61	6.38	NSA	NOOS

GR-TR Network KPIs

Table 18 contains the test results for all cells in the GR-TR CBC. UDP tests started with a large amount of data transmission to push the capacity limits. Tests were repeated by reducing the speed value due to the stability problems and the stopping of the data transmissions. While selecting the cell edge location, the recommended signal level was taken into consideration. During the tests, it has been noted that at certain times the UE lost the coverage and the TCP UL test did not start. Afterwards, it has been decided to perform Cell Edge tests at locations with better radio conditions. Even in such locations, the TCP UL speed level was measured very low. We believe this is related to the uplink sensitivity of the phone being used. UE position was same for all the tests performed in the car.

Table 18: GR-TR Network KPIs

#	Test Case (TC) Name	UL / DL	TCP / UDP	RSRP [dbm]	SINR [db]	Average throughput [Mbps] / Latency [ms]	Peak throughput [Mbps] / Latency [ms]	10th Percentile throughput [Mbps] / Latency [ms]	90th Percentile throughput [Mbps] / Latency [ms]	Average Spectral Efficiency (b/s/Hz)	NSA/ SA TC-related	MNO
KPI_AG1	**DL Data Throughput of Single User (Mbps) - stationary / Central**	**DL**	TCP & UDP	LTE Serving cell average RSRP EDIPS1: -73 EDIPS2: -70 IPSLA1: -84 IPSLA2: -79 EDIPY1: -93 EDIPY2: -71 NR Serving cell average RSRP EDIPS1: -67 EDIPS2: -71 IPSLA1: -84 IPSLA2: -85 EDIPY1: -78 EDIPY2: -72	LTE Serving cell average SINR EDIPS1: 26,5 EDIPS2: 24,7 IPSLA1: 20,9 IPSLA2: 30,3 EDIPY1: 20,6 EDIPY2: 25,7 NR Serving cell average SINR EDIPS1: 26 EDIPS2: 20,8 IPSLA1: 13,9 IPSLA2: 13,4 EDIPY1: 17,8 EDIPY2: 18,8	TCP throughput EDIPS1: 708 EDIPS2: 684 IPSLA1: 892 IPSLA2: 892 EDIPY1: 627 EDIPY2: 593 UDP throughput EDIPS1: 526 EDIPS2: 707 IPSLA1: 965 IPSLA2: 893 EDIPY1: 744 EDIPY2: 704	TCP throughput EDIPS1: 863 EDIPS2: 862 IPSLA1: 1046 IPSLA2: 986 EDIPY1: 772 EDIPY2: 793 UDP throughput EDIPS1: 636 EDIPS2: 749 IPSLA1: 1026 IPSLA2: 988 EDIPY1: 841 EDIPY2: 743	TCP throughput EDIPS1: 451 EDIPS2: 419 IPSLA1: 757 IPSLA2: 851 EDIPY1: 436 EDIPY2: 323 UDP throughput EDIPS1: 454 EDIPS2: 698 IPSLA1: 950 IPSLA2: 860 EDIPY1: 770 EDIPY2: 704	TCP throughput EDIPS1: 832 EDIPS2: 814 IPSLA1: 1002 IPSLA2: 923 EDIPY1: 749 EDIPY2: 772 UDP throughput EDIPS1: 550 EDIPS2: 727 IPSLA1: 991 IPSLA2: 950 EDIPY1: 827 EDIPY2:720	TCP: EDIPS1: 7,08 EDIPS2: 6,84 IPSLA1: 8,92 IPSLA2: 8,92 EDIPY1: 6,27 EDIPY2: 5,93 UDP: EDIPS1: 5,26 EDIPS2: 7,07 IPSLA1: 9,65 IPSLA2: 8,93 EDIPY1: 7,44 EDIPY2: 7,04	NSA	Turkcell

KPI_AG2	**UL Data Throughput of Single User (Mbps) - stationary / Central**	**UL**	TCP & UDP	LTE Serving cell average RSRP EDIPS1: -72 EDIPS2: -71 IPSLA1: -83 IPSLA2: -81 EDIPY1: -92 EDIPY2: -69 NR Serving cell average RSRP EDIPS1: -68 EDIPS2: -71 IPSLA1: -80 IPSLA2: -84 EDIPY1: -78 EDIPY2: -72	LTE Serving cell average SINR EDIPS1: 24,7 EDIPS2: 24,3 IPSLA1: 35,6 IPSLA2: 23,5 EDIPY1: 17,3 EDIPY2: 23,4 NR Serving cell average SINR EDIPS1: 35,6 EDIPS2: 20,7 IPSLA1: 15,5 IPSLA2: 14,1 EDIPY1: 16,5 EDIPY2: 18,3	TCP throughput EDIPS1: 137 EDIPS2: 136 IPSLA1: 136 IPSLA2: 142 EDIPY1: 102 EDIPY2: 141 UDP throughput EDIPS1: 124 EDIPS2: 128 IPSLA1: 130 IPSLA2: 124 EDIPY1: 111 EDIPY2: 127	TCP throughput EDIPS1: 151 EDIPS2: 156 IPSLA1: 152 IPSLA2:156 EDIPY1: 116 EDIPY2: 156 UDP throughput EDIPS1: 167 EDIPS2: 140 IPSLA1: 137 IPSLA2: 134 EDIPY1: 127 EDIPY2: 136	TCP throughput EDIPS1: 131 EDIPS2: 129 IPSLA1: 127 IPSLA2: 137 EDIPY1: 95 EDIPY2: 134 UDP throughput EDIPS1: 115 EDIPS2: 123 IPSLA1: 127 IPSLA2: 109 EDIPY1: 100 EDIPY2: 123	TCP throughput EDIPS1: 148 EDIPS2: 150 IPSLA1: 147 IPSLA2: 153 EDIPY1: 111 EDIPY2: 152 UDP throughput EDIPS1: 132 EDIPS2: 134 IPSLA1: 135 IPSLA2: 130 EDIPY1: 124 EDIPY2: 133	TCP: EDIPS1: 1,37 EDIPS2: 1,36 IPSLA1: 1,36 IPSLA2: 1,42 EDIPY1: 1,02 EDIPY2: 1,41 UDP: EDIPS1: 1,24 EDIPS2: 1,28 IPSLA1: 1,30 IPSLA2: 1,24 EDIPY1: 1,11 EDIPY2: 1,27	NSA	Turkcell
KPI_AG3	**DL Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP & UDP	LTE Serving cell average RSRP EDIPS1: -107 EDIPS2: -116 IPSLA1: -117 IPSLA2: -113 EDIPY1: -111 EDIPY2: 109 NR Serving cell average RSRP EDIPS1: -105 EDIPS2: -100 IPSLA1: -112 IPSLA2: -105 EDIPY1: -101 EDIPY2: 105	LTE Serving cell average SINR EDIPS1: 9 EDIPS2: 1 IPSLA1: 1 IPSLA2: 4 EDIPY1: 6 EDIPY2: 10 NR Serving cell average SINR EDIPS1: 14 EDIPS2: 20 IPSLA1: 7 IPSLA2: 14 EDIPY1: 17 EDIPY2: 15	TCP throughput EDIPS1: 101 EDIPS2: 89 IPSLA1: 287 IPSLA2: 304 EDIPY1: 309 EDIPY2: 219 UDP throughput EDIPS1: 384 EDIPS2: 442 IPSLA1: 323 IPSLA2: 431 EDIPY1: 412 EDIPY2: 314	TCP throughput EDIPS1: 284 EDIPS2: 552 IPSLA1: 485 IPSLA2: 478 EDIPY1: 427 EDIPY2: 340 UDP throughput EDIPS1: 541 EDIPS2: 527 IPSLA1: 582 IPSLA2: 521 EDIPY1: 480 EDIPY2: 407	TCP throughput EDIPS1: 14 EDIPS2: 0 IPSLA1: 199 IPSLA2: 232 EDIPY1: 143 EDIPY2: 137 UDP throughput EDIPS1: 316 EDIPS2: 413 IPSLA1: 289 IPSLA2: 425 EDIPY1: 385 EDIPY2: 180	TCP throughput EDIPS1: 190 EDIPS2: 214 IPSLA1: 375 IPSLA2: 388 EDIPY1: 411 EDIPY2: 305 UDP throughput EDIPS1: 496 EDIPS2: 503 IPSLA1: 379 IPSLA2: 506 EDIPY1: 471 EDIPY2: 381	TCP: EDIPS1: 1,01 EDIPS2: 0,89 IPSLA1: 2,87 IPSLA2: 3,04 EDIPY1: 3,09 EDIPY2: 2,19 UDP: EDIPS1: 3,84 EDIPS2: 4,42 IPSLA1: 3,23 IPSLA2: 4,31 EDIPY1: 4,12 EDIPY2: 3,14	NSA	Turkcell
KPI_AG4	**UL Data Throughput of Single User (Mbps) - stationary / Cell Edge**	**UL**	TCP & UDP	LTE Serving cell average RSRP EDIPS1: -110 EDIPS2: 111 IPSLA1: -105 IPSLA2: -114 EDIPY1: -115 EDIPY2: -113	LTE Serving cell average SINR EDIPS1: 6 EDIPS2: 5 IPSLA1: 11 IPSLA2: 4 EDIPY1: 4 EDIPY2: 6	TCP throughput EDIPS1: 0,08 EDIPS2: 0,12 IPSLA1: 0,10 IPSLA2: 0,05 EDIPY1: 0,05 EDIPY2: 0,04	TCP throughput EDIPS1: 0,34 EDIPS2: 0,63 IPSLA1: 0,34 IPSLA2: 0,12 EDIPY1:0,37 EDIPY2:0,12	TCP throughput EDIPS1: 0,01 EDIPS2: 0 IPSLA1: 0,05 IPSLA2: 0,03 EDIPY1: 0,03 EDIPY2:	TCP throughput EDIPS1: 0,21 EDIPS2: 0,21 IPSLA1: 0,14 IPSLA2: 0,07 EDIPY1: 0,06 EDIPY2:	TCP: EDIPS1: 0 EDIPS2: 0 IPSLA1: 0 IPSLA2: 0 EDIPY1: 0 EDIPY2: 0	NSA	Turkcell

				NR Serving cell average RSRP EDIPS1: -107 EDIPS2: -100 IPSLA1: -105 IPSLA2: -100 EDIPY1: -103 EDIPY2: -104	NR Serving cell average SINR EDIPS1: 12 EDIPS2: 20 IPSLA1: 14 IPSLA2: 20 EDIPY1: 15 EDIPY2: 15	UDP throughput EDIPS1: 11 EDIPS2: 7 IPSLA1: 2 IPSLA2: 10 EDIPY1: 2 EDIPY2: 4	UDP throughput EDIPS1: 18 EDIPS2: 8 IPSLA1: 18 IPSLA2: 14 EDIPY1: 10 EDIPY2: 7	0,01 UDP throughput EDIPS1: 9 EDIPS2: 5 IPSLA1: 0,79 IPSLA2: 8,24 EDIPY1: 1 EDIPY2: 2	0,06 UDP throughput EDIPS1: 12 EDIPS2: 8 IPSLA1: 3 IPSLA2: 12 EDIPY1: 7 EDIPY2: 5	UDP: EDIPS1: 0,11 EDIPS2: 0,07 IPSLA1: 0,02 IPSLA2: 0,10 EDIPY1: 0,02 EDIPY2: 0,04		
KPI_AG5	**DL Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	LTE: Max/Min/Ave RSRP EDIPS1: -63/-86/-74 EDIPS2: -63/-109/-89 IPSLA1: IPSLA2: -79/-117/-85 EDIPY1: -80/-102/-91 EDIPY2: -78/-94/-89 NR: Max/Min/Ave RSRP EDIPS1: -59/-84/-70 EDIPS2: -66/-98/-83 IPSLA1: IPSLA2: -77/-100/-87 EDIPY1: -73/-95/-87 EDIPY2: -70/-94/-88	LTE: Max/Min/Ave SINR EDIPS1: 40/14/23 EDIPS2: 37/7/21 IPSLA1: IPSLA2: 37/2/27 EDIPY1: 33/9/23 EDIPY2: 32/20/22 NR: Max/Min/Ave SINR EDIPS1: 36/-5/25 EDIPS2: 26/-5/15 IPSLA1: IPSLA2: 16/-11/7 EDIPY1: 26/-6/10 EDIPY2: 27/11/16	TCP throughput EDIPS1: 682 EDIPS2: 540 IPSLA1: IPSLA2: 562 EDIPY1: 550 EDIPY2: 229	TCP throughput EDIPS1: 864 EDIPS2: 838 IPSLA1: IPSLA2: 839 EDIPY1: 739 EDIPY2: 684	TCP throughput EDIPS1: 417 EDIPS2: 308 IPSLA1: IPSLA2: 320 EDIPY1: 332 EDIPY2: 138	TCP throughput EDIPS1: 861 EDIPS2: 696 IPSLA1: IPSLA2: 741 EDIPY1: 679 EDIPY2: 419	TCP EDIPS1: 6,82 EDIPS2: 5,40 IPSLA1: - IPSLA2: 5,62 EDIPY1: 5,50 EDIPY2: 2,29	NSA	Turkcell
KPI_AG6	**UL Data Throughput of Single User (Mbps) - mobile**	**UL**	TCP	LTE: Max/Min/Ave RSRP EDIPS1: -62/-87/-74 EDIPS2: -65/-108/-91 IPSLA1: IPSLA2: -78/-115/-90 EDIPY1: -80/-110/-91 EDIPY2: -69/-112/-89 NR: Max/Min/Ave RSRP EDIPS1: -59/-83/-70 EDIPS2: -63/-98/-83 IPSLA1: IPSLA2: -82/-100/-89	LTE: Max/Min/Ave SINR EDIPS1: 28/11/22 EDIPS2: 28/9/18 IPSLA1: IPSLA2: 29/3/20 EDIPY1: 26/7/20 EDIPY2: 30/7/20 NR: Max/Min/Ave SINR EDIPS1: 35/1/25 EDIPS2: 32/-4/16 IPSLA1: IPSLA2: 18/-9/5	TCP throughput EDIPS1: 123 EDIPS2: 75 IPSLA1: IPSLA2: 65 EDIPY1: 87 EDIPY2: 33	TCP throughput EDIPS1: 146 EDIPS2: 152 IPSLA1: IPSLA2: 125 EDIPY1: 154 EDIPY2: 91	TCP throughput EDIPS1: 105 EDIPS2: 38 IPSLA1: IPSLA2: 34 EDIPY1: 51 EDIPY2: 10	TCP throughput EDIPS1: 142 EDIPS2: 129 IPSLA1: IPSLA2: 100 EDIPY1: 128 EDIPY2: 51	TCP EDIPS1: 1,23 EDIPS2: 0,75 IPSLA1: IPSLA2: 0,65 EDIPY1: 0,87 EDIPY2: 0,33	NSA	Turkcell

				EDIPY1: -75/-96/-85 EDIPY2: -70/-103/-85	EDIPY1: 28/6/12 EDIPY2: 27/6/18							
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING	LTE Serving cell average RSRP EDIPS1: -72 EDIPS2: -73 IPSLA1: -90 IPSLA2: -80 EDIPY1: -92 EDIPY2: -70 NR Serving cell average RSRP EDIPS1: -72 EDIPS2: -71 IPSLA1: -80 IPSLA2: -85 EDIPY1: -87 EDIPY2: -76	LTE Serving cell average SINR EDIPS1: 23 EDIPS2: 24 IPSLA1: 18 IPSLA2: 23 EDIPY1: 18 EDIPY2: 24 NR Serving cell average SINR EDIPS1: 37 EDIPS2: 21 IPSLA1: 13 IPSLA2: 13 EDIPY1: 12 EDIPY2: 19	Ping_Size: 32 EDIPS1: 18 EDIPS2: 29 IPSLA1: 27 IPSLA2: 28 EDIPY1: 26 EDIPY2: 26 Ping_Size: 1350 EDIPS1: 30 EDIPS2: 33 IPSLA1: 33 IPSLA2: 34 EDIPY1: 32 EDIPY2: 31	Ping_Size: 32 EDIPS1: 140 EDIPS2: 130 IPSLA1: 33 IPSLA2: 35 EDIPY1: 120 EDIPY2: 32 Ping_Size: 1350 EDIPS1: 89 EDIPS2: 39 IPSLA1:42 IPSLA2:150 EDIPY1: 42 EDIPY2: 39	Ping_Size: 32 EDIPS1: 15 EDIPS2: 26 IPSLA1: 25 IPSLA2: 25 EDIPY1: 23 EDIPY2: 23 Ping_Size: 1350 EDIPS1: 26 EDIPS2: 31 IPSLA1: 30 IPSLA2: 32 EDIPY1: 29 EDIPY2: 29	Ping_Size: 32 EDIPS1: 20 EDIPS2: 30 IPSLA1: 30 IPSLA2: 32 EDIPY1: 27 EDIPY2: 28 Ping_Size: 1350 EDIPS1: 33 EDIPS2: 37 IPSLA1: 38 IPSLA2: 37 EDIPY1: 34 EDIPY2: 32	N/A	NSA	Turkcell
KPI_AG8	**Packet Loss Rate (%) - mobile**	**UL**	UDP	RSRP info not available in pcap data	SINR info not available in pcap data	Greece to Turkey = 0,931% Turkey to Greece = 0,027%				N/A	NSA	Turkcell Cosmote
KPI_AG9		**DL**	UDP	RSRP info not available in pcap data	SINR info not available in pcap data	Greece to Turkey = 0.046% Turkey to Greece = 0,013%				N/A	NSA	Turkcell Cosmote

GR measurements

#	Test Case (TC) Name	UL / DL	TCP / UDP	RSRP [dbm]	SINR [db]	Average throughput [Mbps] / Latency [ms]	Peak throughput [Mbps] / Latency [ms]	10th Percentile throughput [Mbps] / Latency [ms]	90th Percentile throughput [Mbps] / Latency [ms]	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO

KPI_AG1	**Data Throughput of Single User (Mbps) - stationary / Central**	**DL**	**TCP & UDP**	**LTE Serving cell average RSRP -86,4** **NR Serving cell average RSRP -90**	LTE Serving cell average SINR 27,4 NR Serving cell average SINR 20.1	TCP throughput 631 UDP throughput 820	TCP throughput 791 UDP throughput 934	TCP throughput 505 UDP throughput 597	TCP throughput 710 UDP throughput 860	TCP throughput 6.31 UDP throughput 8,20	NSA	Cosmote
KPI_AG2		**UL**	TCP & UDP	LTE Serving cell average RSRP -79.2 NR Serving cell average RSRP -80.6	LTE Serving cell average SINR 27,4 NR Serving cell average SINR 34.9	TCP throughput 65.5 UDP throughput 120.6	TCP throughput 109.2 UDP throughput 137.2	TCP throughput 63 UDP throughput 87	TCP throughput 99 UDP throughput 123	TCP throughput 0.66 UDP throughput 1.21	NSA	Cosmote
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	LTE Serving cell average RSRP -93.3 NR Serving cell average RSRP -97	LTE Serving cell average SINR 25.1 NR Serving cell average SINR 23,6	TCP throughput 342	TCP throughput 620	TCP throughput 397	TCP throughput 560	TCP throughput 3.42	NSA	Cosmote
KPI_AG6		**UL**	TCP	LTE Serving cell average RSRP -93.5 NR Serving cell average RSRP -97.2	LTE Serving cell average SINR NR Serving cell average SINR 24.6	TCP throughput 19.3	TCP throughput 56.9	TCP throughput 36.5	TCP throughput 50	TCP throughput 0.19	NSA	Cosmote
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING	LTE Serving cell average RSRP -95.5 NR Serving cell average RSRP -90.9	LTE Serving cell average SINR 29.2 NR Serving cell average SINR 19.3	Ping_Size: 32 No Load: 19.93 Load: 14.96 Ping_Size: 1500 No Load: 26.28 Load:21.8	Ping_Size: 32 No Load :11 Load:8 Ping_Size: 1500 No Load:15 Load: 14			N/A	NSA	Cosmote

All outputs of the tests can be accessed from this link: [5G-MOBIX - D3.7_Appendix-Results_GR-TR - All Documents (sharepoint.com)]

2.8.2. DE Network KPIs

Table 19 provides the values of the common set of KPIs as measured at the DE deployed 5G networks.

Table 19: DE Network KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP UDP	284,46 58,99	330,22 60,91	252,50 59,58	313,20 60,3	3,16	NSA	DT
KPI_AG1			TCP UDP	166,17 44,09	306,66 49,7	50,60 44,77	272,42 45,15	1,29	NSA	O2
KPI_AG2		**UL**	TCP UDP	47,21 19,64	56,54 21,37	40,02 19,67	53,19 20.23	0,52	NSA	DT
KPI_AG2			TCP UDP	27,17 5,89	58,19 6,73	13,16 5,86	46,15 6,09	0,30	NSA	O2
KPI_AG3	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP UDP	144,75 19,62	312,72 21,39	49,91 19,78	239,07 20,11	1,61	NSA	DT
KPI_AG3			TCP UDP	43,30 14,01	101,05 17,14	18,09 12,59	70,12 15,05	0,48	NSA	O2
KPI_AG4		**UL**	TCP UDP	0,94 0,95	5,40 1,02	0,86 0,94	1,01 0.98	0,01	NSA	DT
KPI_AG4			TCP UDP	44,14 9,84	57,20 11,21	30,29 9,87	53,31 10,101	0,49	NSA	O2
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP UDP	112,31 19,33	278,20 36,4	49,42 18,32	195,05 20,2	1,24	NSA	DT
KPI_AG5			TCP UDP	85,69 14,58	307,44 17,93	29,53 14,49	143,49 15,06	0,95	NSA	O2
KPI_AG6		**UL**	TCP UDP	20,35 23,84	141,85 44,83	0,89 18,74	40,25 25,55	0,23	NSA	DT
KPI_AG6			TCP UDP	16,89 19,82	72,62 56	1,59 0,4	45,29 34	0,19	NSA	O2
KPI_AG7		**DL**	PING	20,42	61	18	23	N/A	NSA	DT

KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING	91,24	362	47	194	N/A	NSA	O2
KPI_AG8	**Packet Loss Rate (%) - mobile**	**UL**	UDP	2,51	59	0	8,49	N/A	NSA	DT
KPI_AG8			UDP	0,24	7,7	0	0.6	N/A	NSA	O2
KPI_AG9		**DL**	UDP	1,64	61.1	0	3.6	N/A	NSA	DT
KPI_AG9			UDP	1,19	61,67	0	2,14	N/A	NSA	O2

Regarding the UDP tests, lightweight traffic conditions (without saturating the channel and thus avoiding packet losses) have been modeled and analyzed. Therefore 20% of TCP data rates at good conditions have been used as the UDP data rate. That is why some UDP values are lower than TCP values.

2.8.3. FI Network KPIs

In the FI-TS, the trials were targeted for use by both research 5G NSA/SA networks (operated by AALTO) and commercial 5G NSA networks (operated by Telia and Elisa). Ultimately, the usage of the commercial networks became more prominent in the trials due to equipment failure in the research networks. As result the agnostic KPI measurements are presented only for the commercial networks which are later also used for the FI-TS specific (user story) trials. The measurement results (provided in

Table 20) were only conducted with drive tests (mobile UE) using the Keysight Nemo tool. It should be noted that as these production networks with shared usage, the results below are not for networks with a single user. Moreover, the average spectral efficiencies are evaluated considering the spectrum allocation of 130 MHz for each operator in the 3.5 GHz (n78) 5G band.

Table 20: FI Network KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	RSRP @point of measurement	SINR @point of measurement	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	Average NR RSRP -93	Average NR SINR 12.7	83	190	30	121	0.64	NSA	Telia
KPI_AG5				Average NR RSRP -92	Average NR SINR 13.9	395	848	81	677	3.04	NSA	Elisa
KPI_AG5			UDP	Average NR RSRP -92	Average NR SINR 13.9	391	992	79	790	3.01	NSA	Elisa
KPI_AG6	**Data Throughput of Single User (Mbps) - mobile**	**UL**	TCP	N/A	N/A	30	55	11	49	0.23	NSA	Telia
KPI_AG6				N/A	N/A	32	113	0	113	0.25	NSA	Elisa
KPI_AG6			UDP	N/A	N/A	34	131	6	60	0.26	NSA	Telia
KPI_AG6				N/A	N/A	54	100	23	81	0.42	NSA	Elisa
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING	N/A	N/A	80	3708	11	158	N/A	NSA	Telia
KPI_AG7		**DL**	PING	N/A	N/A	38	412	22	69	N/A	NSA	Elisa

2.8.4. FR Network KPIs

Table 21 provides the values of the common set of KPIs as measured at the FR deployed 5G networks.

Table 21: FR Network KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP UDP	35,7 1,0	58 1,1	34,9 0,98	36,5 1,02	1,9	NSA	Bouygues
KPI_AG1			TCP	13,6	46,9	0,0	30,2	0,14	NSA mmWave	TDF
KPI_AG2		**UL**	TCP UDP	40,5 1,0	86,9 1,0	14,2 0,98	67,3 1,0	2	NSA	Bouygues
KPI_AG2			TCP	10,2	76,05	0,0	34	0,1	NSA mmWave	TDF
KPI_AG3	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP UDP	34,4 1,0	40.6 1.1	31.2 0.98	36.2 1.0	1,7	NSA	Bouygues
KPI_AG4		**UL**	TCP & UDP	35,8 1,0	57,9 1,0	23,2 0,98	46,3 1,0	1,8	NSA	Bouygues
KPI_AG5	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	34.7	58.1	31.2	36.5	1,7	NSA	Bouygues
KPI_AG5			TCP	12.4	51	0	30.1	0,12	NSA mmWave	TDF
KPI_AG6		**UL**	TCP	40,2	87,8	17,2	63,7	2	NSA	Bouygues
KPI_AG6			TCP	27,3	89,8	0	64,2	0,27	NSA mmWave	TDF
KPI_AG7	**User Plane Latency (e2e)**	**DL**	PING	26	562	17,4	27,6	N/A	NSA	Bouygues
KPI_AG8	**Packet Loss Rate (%) - mobile**	**UL**	UDP	0.03	2.3	0	0	N/A	NSA	Bouygues
KPI_AG9		**DL**	UDP	0	0	0	0	N/A	NSA	Bouygues

2.8.5. NL Network KPIs

Table 22 provides the values of the common set of KPIs as measured at the NL deployed 5G networks.

Table 22: NL Network KPIs

	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	Signal strength	MNO
KPI_AG 1	Data Throughput of Single User (Mbps) -Stationary / Central	DL	TCP & UDP (100Mhz)	443 mbps (TCP) 437 mbps (UDP)	571 mpbs (TCP) 513 mps (UDP)	N/A	N/A	4,4	SA	N/A	TNO
KPI_AG 1	Data Throughput of Single User (Mbps) -Stationary / Central	DL	TCP (100Mhz)	441 mbps	N/A	N/A	N/A	4,4	SA	RSRP: -73dbm SINR: 37db	KPN
KPI_AG 2	Data Throughput of Single User (Mbps) -Stationary / Central	UL	TCP & UDP (100Mhz)	42 mbps (TCP) 49 mbps (UDP)	52 mbps (TCP) 56 mbps (UDP)	N/A	N/A	0,4	SA	N/A	TNO
KPI_AG 2	Data Throughput of Single User (Mbps) -Stationary / Central	UL	TCP (100Mhz)	82 mbps	N/A	N/A	N/A	0,8	SA	RSRP: -73dbm SINR: 37db	KPN
KPI_AG 3	Data Throughput of Single User (Mbps) - stationary/ Cell Edge	DL	TCP (100Mhz)	165 mbps	297 mbps	88 mbps	264 mbps	1,7	SA	RSRP: -115dbm SINR: 9db	KPN
KPI_AG 4	Data Throughput of Single User (Mbps) - stationary/ Cell Edge	UL	TCP (100Mhz)	19 mbs	40 mbps	10 mbps	36 mbps	0,2	SA	RSRP: -118dbm SINR: 6db	KPN
KPI_AG 5	Data Throughput of Single User (Mbps) - mobile	DL	TCP (100Mhz)	95 mbps	238 mbps	3,1 mbps	171 mbps	0,95	SA	See plots	TNO
KPI_AG 5	Data Throughput of Single User (Mbps) - mobile	DL	TCP (100Mhz)	191 mbps	299 mbps	90 mbps	256 mbps	1,91	SA	See plots	KPN
KPI_AG 6	Data Throughput of Single User (Mbps) - mobile	UL	TCP (20Mhz)	8,5 mbps	13 mbps	2	12	0,43	SA	See plots	TNO
KPI_AG 6	Data Throughput of Single User (Mbps) - mobile	UL	TCP (100Mhz)	48 mbps	81 mbps	10 mbps	78 mbps	0,48	SA	See plots	KPN
KPI_AG 7	User Plane Latency (e2e)	DL	PING (100Mhz)	LBO: 5,8 ms (RTT) Core routed: 13,9 ms (RTT)	LBO: 8,5 ms (RTT) Core routed: 27,2 ms (RTT)	N/A	N/A	N/A	SA	N/A	TNO
KPI_AG 7	User Plane Latency (e2e)	DL	PING (100Mhz) 1408 bytes mobile	16,0 ms	392,0 ms	12,0 ms	19,2 ms	N/A	SA	rsrp: between-75dbm and -133 dbm	KPN

2.8.6. CN Network KPIs

Table 23 provides the values of the common set of KPIs as measured at the CN deployed 5G networks.

Table 23: CN Network KPIs

	CBC/TS_MS	Test Case (TC) Name	UL / DL	TCP / UDP	Average	Peak	10th Percentile	90th Percentile	Average Spectral Efficiency (b/s/Hz)	NSA/SA TC-related	MNO
KPI_AG1	CN	**Data Throughput of Single User (Mbps) -Stationary / Central**	**DL**	TCP & UDP	TCP: 524 UDP:598	TCP: 854 UDP: 949	TCP: 254 UDP: 221	TCP: 711 UDP: 893	N/A	SA	China Mobile
KPI_AG2	CN		**UL**	TCP & UDP	TCP: 102 UDP: 108	TCP: 130 UDP: 140	TCP: 112 UDP: 117	TCP: 126 UDP: 137	N/A	SA	China Mobile
KPI_AG3	CN	**Data Throughput of Single User (Mbps) - stationary/ Cell Edge**	**DL**	TCP & UDP	TCP: 16.057 UDP: 12.320	TCP: 50.179 UDP: 43.219	TCP:5.573 UDP: 3.322	TCP: 34.628 UDP: 32.305	N/A	SA	China Mobile
KPI_AG4	CN		**UL**	TCP & UDP	TCP: 4.668 UDP: 7.211	TCP: 29.539 UDP: 23.390	TCP: 2.964 UDP: 1.034	TCP: 6.996 UDP: 15.852	N/A	SA	China Mobile
KPI_AG5	CN	**Data Throughput of Single User (Mbps) - mobile**	**DL**	TCP	359.243	540.772	138.030	510.465	N/A	SA	China Mobile
KPI_AG6	CN		**UL**	TCP	106.310	138.039	102.024	129.701	N/A	SA	China Mobile
KPI_AG7	CN	**User Plane Latency (e2e)**	**DL**	PING	Ping_Size: 40 22 ms Ping_Size: 1400 25 ms	Ping_Size: 40 60 ms Ping_Size: 1400 120 ms	Ping_Size: 40 16ms Ping_Size: 1400 22 ms	Ping_Size: 40 33 ms Ping_Size: 1400 28 ms	N/A	SA	China Mobile

2.8.7. Insights based on common network KPIs

In the previous sections, measurements are shown from the different trial sites and cross border corridors. Each of the sites has a different network setup, making it difficult to compare absolute numbers. We can however compare some ratio's helping to gain a better understanding of the current capabilities of 5G networks. The spectral efficiency gives us the amount of bits per second for each Hertz used to transmit. We see that the efficiency goes down moving from cell center to cell edge (see Figure 7). This is especially true for the uplink. The spectral efficiency at the cell center is for the downlink at average 5 times higher than the uplink. Moving to the cell edge, the spectral efficiency for the downlink is at average 9 times higher than the uplink. This shows that a bottleneck is likely to occur at the cell edge in the uplink.

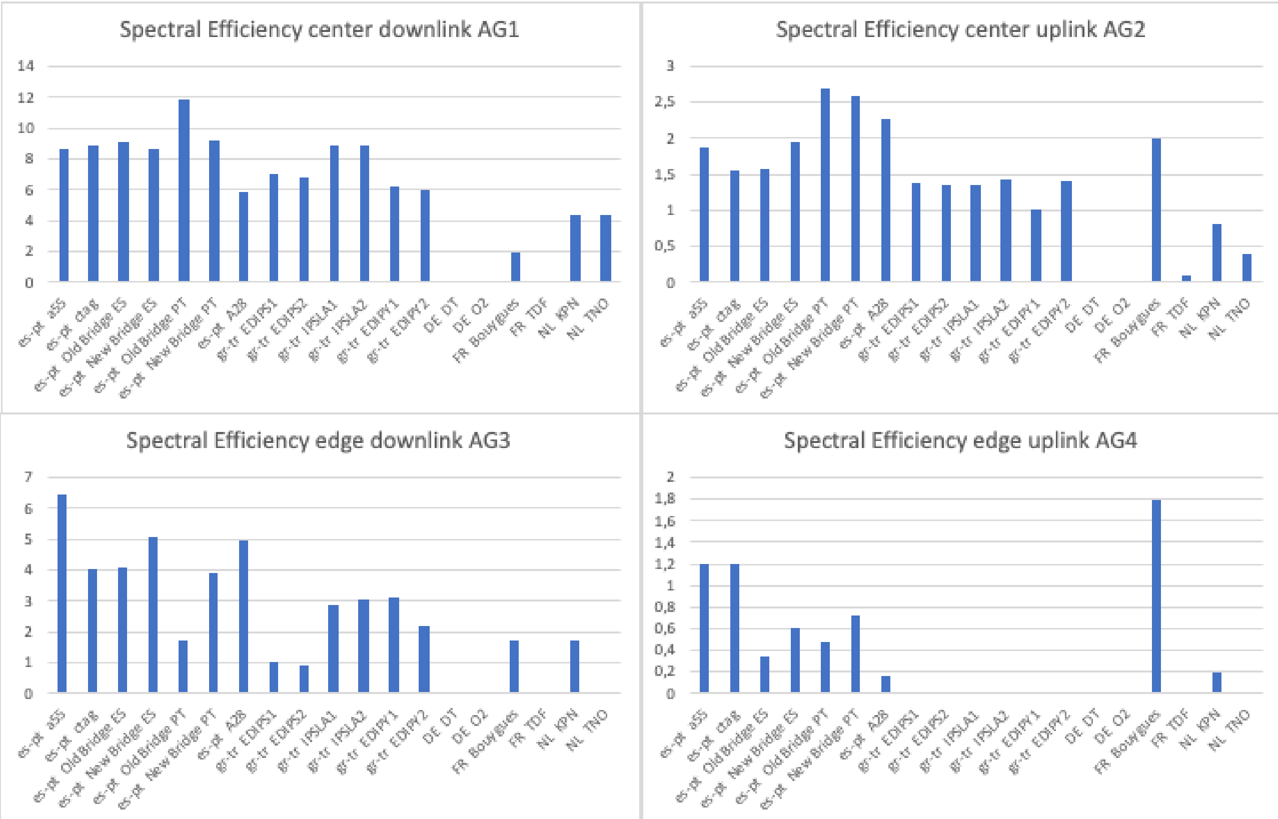


Figure 7: Spectral efficiency up and down at both cell-center and cell-edge

Since most use cases need to work always, being at the cell-edge or cell-center, networks need to be designed such that they offer enough capacity at the cell edge. The use cases for connected and automated mobility will need to have at least as much bandwidth for the uplink as is needed for the downlink, if not more. One of the most demanding use cases for our mobile networks is tele-operations, requiring more uplink bandwidth than downlink. The spectral efficiency however at almost all sites drops below 1 b/s/Hz for the uplink at the cell edge. In absolute numbers the uplink bandwidth at the cell edge varies between

0,04 and 48 Mbps with an average of 17 Mbps over all networks. This is definitely too low for some of the use cases and we need to also consider that for most trial sites these numbers are without load of additional users. To overcome this issue, we either need to: (1) define smaller cells; (2) add extra spectrum or (3) change the uplink/downlink ratio.

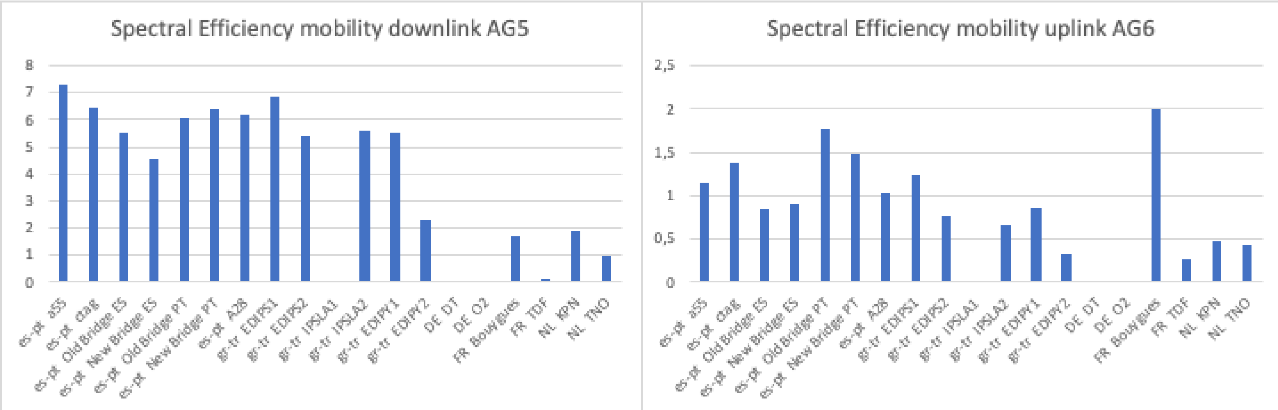


Figure 8: Spectral efficiency up and downlink while driving

Also, measurements have been performed while driving the same trajectory as the use cases (see Figure 8). At average over the different trial sites the uplink spectral efficiency over all trial sites is 0,9 b/s/Hz and at average 4.9 times smaller than the downlink. With the exception of the France trial site, all other trial sites have a downlink-oriented network. This is to be expected since most networks use the 3,5GHz band. Most operators or countries follow a downlink/uplink ratio of 4:1, targeting regular internet users. For some of the CAM use cases we see however a tendency for larger uplink bandwidts compared to the downlink (e.g. tele-operations).

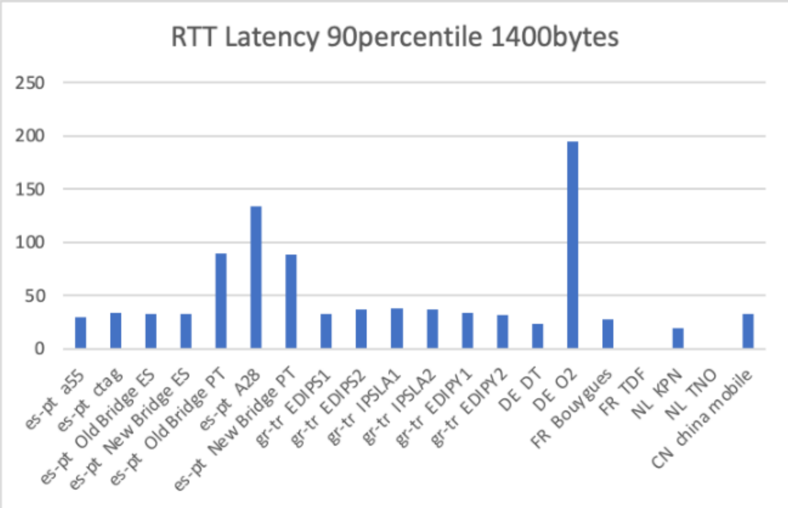


Figure 9: Round trip latency 1400 bytes 90percentile

When comparing the latency, it is considered good practice to evaluate the maximum latency of 90% to 99% of all samples, filtering out the largest samples. Comparing the different networks, the 90 percentile round trip latency varies between 19 and 194 ms and at average is 53ms (see Figure 9). When comparing only the average latencies the mean round trip latency varies between 16 and 91 ms and at average is 36ms. At some sites the difference between the average and 90 percentile latency is rather large. Normally this is due to the variation in the cellular link and might be due to: (1) high network load or (2) bad signal strength.

3. 5G NETWORK ARCHITECTURE – INSIGHTS FOR CROSS-BORDER DEPLOYMENTS

Within 5G-Mobix, different network technologies have been considered to solve the cross-border issues identified. Although, at the time of writing this deliverable, tests are still ongoing. In this section they are listed, described and where possible the first testing results are given. The following technologies are considered:

- Release with redirect
- Release and redirect using the S10 or N14 interface
- S1/N2 handover using the S10 or N14 interface
- Multi-sim setup for SA and NSA
- Continuity measures
- Slicing
- Predictive QoS
- Satellite fall-back
- Local break-out roaming, compared to Home routed roaming using NSA network
- Local break-out roaming, compared to Home routed roaming using SA network
- Comparing internet based with direct connect peering between operators
- Angular domain positioning using mmWave
- mmWave for CAM

3.1. Release with redirect

Release with Redirect describes a procedure where the UE needs to re-attach and re-authenticate to the new network. No context information is transferred between gNB's or core networks regarding the current session. It therefore results in a service interruption as the UE attaches to the target gNB, which has to authenticate and setup a new bearer session.

The architecture is identical to the default roaming architecture where the S6a interface is added between the visited Mobility Management Entity (MME) and the Home Subscriber Server (HSS) on the control plane and the S8 interface between visited Serving Gateway (S-GW) and the home Packet Gateway (P-GW) for the user plane (see Figure 10). The source gNB orders the UE to conduct a Release with Redirect procedure and provides the Absolute Radio Frequency Channel Number (ARFCN) and Physical Cell Identifier (PCI) of the target gNB in the target PLMN to the UE. This information must therefore be known in the source gNB. The source gNB does not need to know how it can reach the target gNB as they do not need to exchange any information for the Release with Redirect procedure. The UE will search for the target gNB according to the provided information and attach to it. This will only succeed if the PLMN is included in the Equivalent PLMN list the UE previously received within a Tracking Area Update (TAU) in the HPLMN.

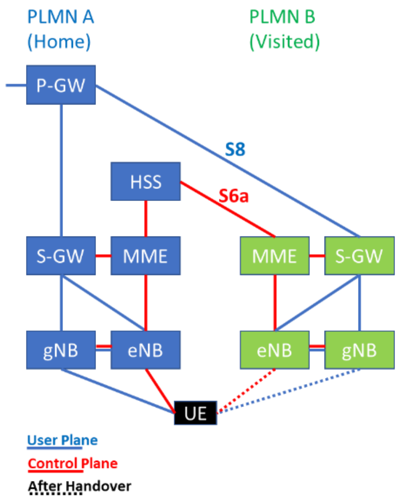


Figure 10: Release with Redirect Architecture without S10 Interface

3.1.1. Standards

TS 36.304 [14] section 5.2.7 specifies the UE-side of the Release with Redirect procedure and TS 36.331 [15] Sections 5.3.8.3 & 5.3.12 the interaction between UE and gNB. It is not subject to standardization what triggers the gNB to send a Release with Redirect message to the UE. Radio equipment used in trials allows to use the measurement reports, normally intended for handover, to trigger a Release with Redirect.

It is not fully clear how network and UE will react if the packet data network session cannot be resumed as the core context cannot be transferred from the source to the target network as there is no S10 interface between them. The working assumption, to be confirmed in trials, is that the packet data network connection is re-established. In case of Local Break-Out (LBO) roaming, it would result in using a P-GW in the VPLMN.

3.1.2. Learnings

The function release with redirect is being tested with a 5G SA network within the Dutch trial site. Since there are no vendor solutions yet enabling SA roaming, effort went into adding code to an opensource solution. For the gNB's a vendor product from Ericsson is used. This product supports a solution called: "Mobility Control at Poor Coverage". Since the standard only specifies the "release with redirect" message and not when this is triggered, this solution is vendor specific. In this case an A5 event needs to be triggered before the message is send. Before an A5 event can be reached the UE must be instructed to measure certain frequencies. This is done when the A2 event is triggered. At this moment tests are performed to get this functionality in a working order. Since after the initial roaming tests there was still some time left the Dutch trial site agreed to try and extend the functionality further, taking the risk it cannot be finished before the end of the project.

Impact for MNO: MNOs need to exchange ARFCN and PCI information of neighbouring cells. Although the PCI information is not necessarily shared in the "release and redirect" message the PCI does need to be configured in the gNB. The base stations at the borders need to be configured with special configurations, changing over time as the network evolves. As of yet, it is unclear how much configuration work can be automated. For the exchange of radio information across operators, it is preferred to introduce an automated procedure among operators to exchange this information.

Currently MNO's have specific roaming agreements with other MNO's. In these agreements traffic volumes play an important role. For this reason, special steering mechanisms are in place to try and direct subscribers to a certain network. These steering mechanisms are UE based and not network based. The UE is directed to another network by denying access to certain visited networks and by in-time updating the SIM information with a preferred visited PLMN. These steering mechanisms will collide with cross border network based steering mechanisms and can potentially cause extra disconnect time.

Impact for OEM: Vehicles approaching a border where a handover has been configured should be aware of specific measures taken. It is expected that as vehicles start to rely on mobile networks, special in-vehicle mechanisms and configurations are introduced to minimize disconnect times across borders. These special mechanisms and configurations can conflict with network-based handovers. For instance, when an OEM has a setup where the modem is steered towards a certain network at a certain trigger, a ping pong effect can occur when this switch collides with a network based steering mechanism.

3.2. Release and redirect using the S10 or N14 interface

3.2.1. Standards

Release with Redirect using the S10 interface describes a procedure that is normally related to idle mode mobility, as it does not transfer context information between the source and target gNB. It therefore results in a service interruption as the UE attaches to the target gNB in idle mode and has then to transition to connected mode. The S10 interface connects two MME's and is most commonly used in a plmn network, connecting for instance different regions in a country. In the core network, context information is exchanged between the source and destination core through the S10 interface. The UE, therefore, does not have to initiate the procedure to establish a packet data network connection as the session is resumed.

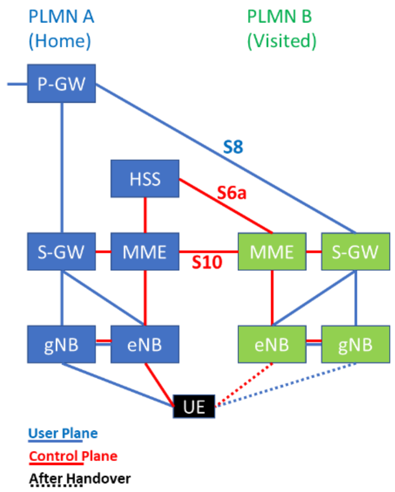


Figure 11: Release with Redirect Architecture with S10 Interface and Home routed Roaming

Figure 11 depicts the Release with Redirect architecture with S10 interface. It is almost identical to the default roaming architecture with the addition of the S10 interface between the MMEs. This corresponds to the Home Routed (HR) roaming architecture, which always applies right after the transition from HPLMN - to the VPLMN as the P-GW never changes during radio handover. A transition to LBO roaming would require a separate step to re-anchor from the home to the visited P-GW (not shown in the figure).

The HO steps are identical to the ones described in section 3.1. In this case, no information is exchanged between the involved gNBs, but after completing the attachment to the target gNB the S10 interface between MMEs will be used to transfer the core network context including adjustment of the route to/from the P-GW to terminate at the new serving cell. This is triggered by a TAU which the UE will initiate once attached to the target gNB. Normal procedures for leg-addition and path switching apply in order to attach to the target gNB and use it for user data transmissions.

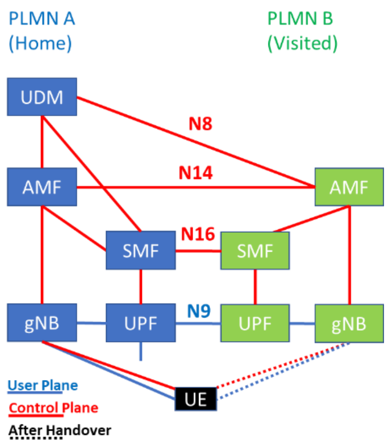


Figure 12: Release with Redirect Architecture with N14 Interface and Home routed Roaming

In the 5G SA architecture (Figure 12), the procedure for home routed roaming follows very similar principles as explained before for the NSA architecture. In the control plane, the N8 interface between home UDM and visited AMF corresponds to the S6a interface between home HSS and visited MME. The additional N16 interface is needed due to the control and user plane split introduced in the 5G SA architecture. In the user plane, the N9 interface between home and visited UPFs correspond to the S8 interface between home P-GW and visited S-GW. In the Release and Redirect procedure in 5G SA, the N14 interface between home and visited AMFs is used in a similar way as with the S10 interface in NSA, as it allows the visited AMF to retrieve context information from the home AMF. In addition, the visited core is made aware of home UPF and UE IP address to speed up the re-establishment of the user plane in the new network.

The same Technical Specifications (TS) as before specify the UE and UE-gNB procedures. It is not subject to standardization what triggers the gNB to send a Release with Redirect message to the UE. Radio equipment used in trials allows to use the measurement reports, normally intended for handover, to trigger a Release with Redirect.

3.2.2. Learnings

Within the project focus is given to the handover solution as described in section 3.3. If time allows this solution will also be tested.

Impact for MNO: Besides the exchange of RAN data between operators, also an extra interface is needed between the cores. Currently the S10 interface is not part of the standard roaming interconnects. The S10 interface is currently not part of the GSMA roaming standardisation between operators. The conflict with the current steering of roaming mechanism has already been described in the previous section and also applies for this solution.

Impact for OEM: The same impact as described under section 3.1.2 applies also here. Care must be taken that network based steering mechanisms don't collide with in-vehicle modem steering mechanisms.

3.3. S1/N2 handover using the S10 or N14 interface

This solution extends the previous described solution, also using the S10 or N14 interface. The main difference is that it allows for a handover of the data session between the source and target network, as seen in Figure 13.

An S1 handover is a normal HO procedure also used within one PLMN when there is no X2 interface between the involved gNBs. It may also include a change of MME, in which case the S10 interface is also used. An Inter-PLMN handover always goes along with a change of MMEs. The same information as for an X2 handover is exchanged between source and target gNB but the MMEs are relaying it. The source gNB asks the target gNB to accept the UE and the target gNB provides its configuration information. This information is provided to the UE so it can adapt, if needed, to the target gNB settings and quickly connect to it.

Nevertheless, it has to detach from the source gNB and then synchronize with the target one where it then performs the random-access procedure. Once this is done, communication is resumed as the source gNB transferred all RAN context information to the target one. Furthermore, the S10 interface is used to conduct the core context transfer and routes are adapted towards the now serving target gNB.

The HO Restriction list must be set in a way that a HO to the target PLMN, even if not being the HPLMN, is not prohibited. It is strictly speaking not required to also have the VPLMN in the EPLMN list, but it is suggested for two reasons: i) in order to assure that the UE also transitions to the target network when in idle mode and ii) because Release with Redirect is often used in case a handover fails.

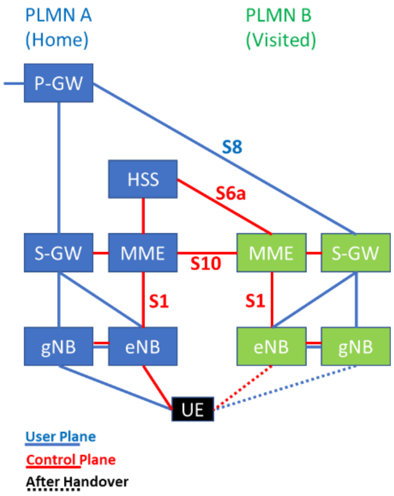


Figure 13: S1 Handover Architecture with Home Routed Roaming (NSA)

In the 5G SA architecture (Figure 14), the N2 handover procedure works in a similar way compared with the S1 handover previously described for NSA. Thus, in addition to facilitating the exchange of context data between the home and visited AMFs, the N14 interface plays a similar role as the S10 by acting as relay to exchange information between the source and target gNBs. The source gNB requests the target gNB to reserve resources for the UE. When the target gNB accepts it, the source gNB sends a 'handover command' to the UE with information about the target network so that the UE can proceed and connect to the new network.

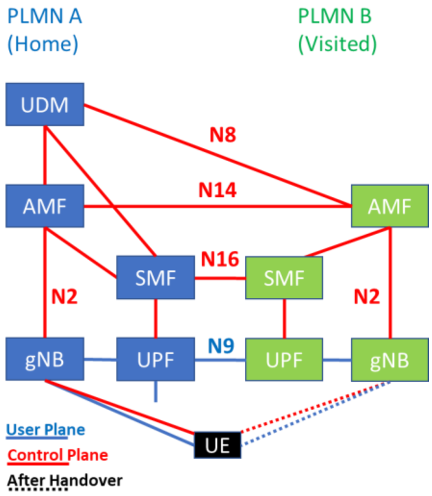


Figure 14: N2 Handover Architecture with Home Routed Roaming (SA)

3.3.1. Standards

TS 36.331 [15] Section 6.3.5 describes the message sent from the gNB to the UE to advice it to measure a certain cell (in this case from a different PLMN) and report the measurement when certain conditions, that can also be configured, are fulfilled. It is up to configuration what event is used to trigger the reporting. A common configuration could rely on the so-called A3 event that is triggered when, among some further conditions, Reference Signals Received Power (RSRP) and/or Reference Signal Received Quality (RSRQ) of the target gNB is above the one of the source gNB.

The HO procedure requires several messages between the MMEs or AMFs for 5G cores. The complete duration of the handover procedure will depend on the delay between the cores of both PLMNs. Cores are normally located at centralized sites far away from country borders, so some delay is expected.

3.3.2. Learnings

This solution is implemented and tested by both the GR-TR CBC and the ES-PT CBC at a real border. Both are using test networks for this. With the GR-TR CBS an Ericsson solution is implemented and with the ES-PT CBC a Nokia solution.

Impact for MNO: The same requirements as for Release with Redirect while using the S10 interface apply. In addition, the e/gNBs need to contain references to each other beyond just the ARFCN and PCI. They must provide the involved MMEs the required identifiers so the information required for handover preparation and execution can be exchanged with the MMEs and the S10 interface between them serving as relay.

Impact for OEM: The impact for the OEM is similar as is with the previous release and redirect solutions. In addition, the disconnect time will be the lowest using these solutions. Looking at our current networks at the border it must be considered thus that it is likely that not the full spectrum will be available before or after the handover. Finding the optimal trigger for a release and redirect is difficult as it is. Making sure all bands at the target gNB will have reception and get connected after the handover in a consistent manner seems to be nearly impossible.

3.4. Multi-sim setup for SA and NSA

Although most professional router implementations offer multi-sim solutions, they all differ in implementation and do not adhere to a certain standard with respect to the multi-sim or multi-modem solution they offer. Within the 5G-Mobix project, three trial sites have tested a common-off-the-shelf router and one trial site has implemented a custom solution. The common-off-the-shelf routers seem to follow the same design principle using a VPN tunnel such that the applications will always see the same GW IP address provided by the router. Although abstracting away the underlying IP connections does reduce complexity at the side of the application, it introduces some other disadvantages which the custom solution tries to overcome. A comparison of the three multi-SIM application within 5G-MOBIX is provided in Table 24.

Table 24: Comparison of multi-SIM solutions

	FR-TS	FI-TS	DE-TS
Key components	1 Pepwave intelligent router and 1 Pepwave fusion box (aggregator)	Multichannel router box (with slots for two 5G modems and 2 SIMs)	Custom solution with two modems and an on-board computer
Methodology	(1) Pepwave router can connect two PLMN links with or without link aggregation functionalities. Besides cellular technologies, WiFi, satcom, ethernet other connection can also be used. (2) Different policies can be used for prioritisation of the connections: signal quality, high bandwidth, low latency etc. (3) Pepwave fusion box, or aggregator, will fuse and re-order received packets (4) Router and fusion box creates a VPN tunnel so that the use of multi-connections becomes transparent from the users.	(1) Multichannel router connects to 2 PLMNs (security using IPSec VPN for both connections) (2) Router creates mobile IP tunnel (MIP) for selection of PLMNs, with MIP GW as the anchor (3) UE-side (in-vehicle LAN) of the router provided with multiple interfaces including GbE and WLAN	(1) Both modems are connected to a different PLMN. (2) An application on the OBU is used to switch between operators based on the location, e.g. as outcome of a prediction function. (3) Each modem has its own application client associated (an MQTT client) using the respective PLMN; when the location is reached by the vehicle the application establishes connection via other modem's MQTT client.
Parameters on which the handover is based	The handover is based following pre-set policy: fixed priority, signal quality, highest bandwidth, lowest delay	PLMN selection based on pre-configured priorities or connection quality value derived from signal strength, latency, RAT priority	Location based PLMN switch on OBU side (UE-driven network switch)
RATs tested	LTE, 5G NR NSA, Satellite	LTE, 5G NR (NSA and SA)	LTE, 5G NR NSA

3.4.1. Standards

The contemporary multi-SIM solutions, such as, those being considered in 5G-MOBIX as described above, are typically based on proprietary solutions, and implemented without standardised support of multi-SIM feature from the associated 3GPP systems. In that case, networks serving a particular multi-SIM device may do so with degraded performance on one or more of the connections. In response to the increased adoption of multi-SIM devices, 3GPP has included in Release 17 an ongoing work item for standardisation of enhanced support of multi-SIM devices (physical or embedded SIMs) associated with multiple 3GPP system, scope being Evolved Packet System (EPS) or 5G System (5GS). This includes study of system impacts of legacy multi-SIM device implementations and potential enhancements on aspects, such as, efficient monitoring of multiple paging channels (of each associated 3GPP system) by a multi-SIM device and coordinated departure of the multi-SIM device from one of the 3GPP systems.

3.4.2. Architecture

Two different architectures have been tested:

1. Common off the shelf routers (COTS)

2. Custom – location based – solution

Both the COTS routers use the same type of architecture based on VPN setup. The custom solution is not using a VPN gateway and uses a location aware application. Both solutions are depicted in Figure 15.

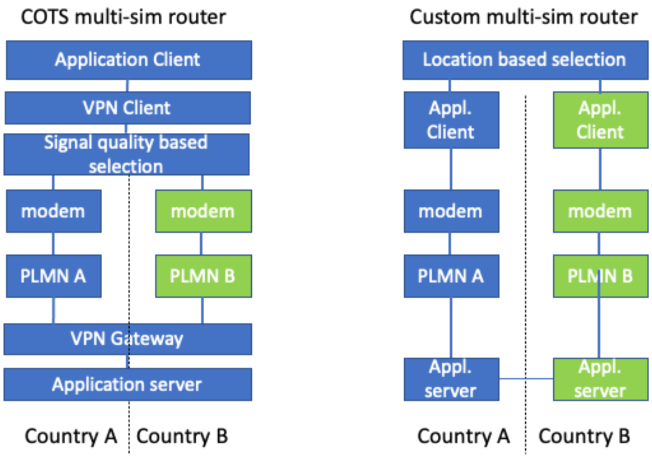


Figure 15: Comparing COTS and custom multi-sim router

There are two distinct differences when comparing both architectures:

1) Traffic routing

2) PLMN selection

The cots-based router hides the multiple PLMN's by using a VPN solution. This way, the application does not need to be aware of multiple underlying networks. No changes are needed to the application. Also is it possible to combine both modem connections and aggregate the traffic. The VPN Gateway however is located in a single country making that traffic will always be routed via that country. The custom multi-sim router presents both PLMN networks to the application, enabling a shorter route but with the implication that the application needs to be aware of both networks.

The cots-based routers have different ways to select the best PLMN. In this case for both implementations the signal quality is used to select the best modem. Each mode has a sim of a different PLMN (as is also the case for the custom solution). The custom solution however needs a central data-source to select a different PLMN. This central data-source has been built up ahead of time, using the learnings of previous road users for the respective PLMN's 5G coverage. As such, the custom solution is based on principles laid out by the 5GAA for providing Predictive QoS in C-V2X [16], however the scope of the custom approach is focused on multiple PLMNs coverage characteristics instead of the single PLMN scope in the 5GAA-based concept.

3.4.3. Learnings

The tests with the cots-based routers have been performed at the Finnish trial site and France trial site. The custom solution was tested at the German trial site.

Learnings from the FR TS tests

FR TS has conducted series of tests in France and at the ES-PT CBC. Tests in France were executed under the Bouygues and Orange 5G networks under a significant coverage overlap. The tests were conducted under relatively "good" conditions: with low vehicle speed (20-30 km/h) and under medium to excellent levels of signal quality. Both the modes of the multi-SIM configuration, passive (link-selection) and link-aggregation, have provided excellent performances with 0% of packet loss rate and without service interruption caused by the change of the network. The results obtained from the ES-PT CBC were significantly different. We first conducted tests using the Single-SIM solution. The results of these single-SIM tests provided showed on average 20 seconds of service interruption time due to handover and roaming procedures. The multi-SIM solution under passive and link-aggregation modes reduce the service interruption time down to 4.7 and 3.7 seconds respectively. While the service interruption time is greatly reduced (4 times), the service interruption time remains large for CAM. The results are encouraging for OEMs that the vehicle can largely reduce service interruption in their own country as well as at the cross border. Concerning impacts to MNOs, as mentioned earlier, 3GPP has ongoing work item for standardisation of enhanced support of multi-SIM devices (physical or embedded SIMs) associated with multiple 3GPP systems. The obtained results are probably showing the limits of UE-based solution and showing the need of further effort from the MNOs.

Although the tested solutions are all proprietary, the following generic statements can be made considering the different solutions:

- The COTS devices work best with a "sim per country", each modem in the router has a SIM for a different country with roaming disabled.
- Both solutions rely on a gateway that aggregates the traffic. This as an "over-the-top" solution, without specific features needed from the mobile network. The larger the distance with the gateway, the larger the delay (although it might be possible multiple gateways can be used with an intelligent selection mechanism).

If a vehicle traverses one single border regularly the multi-sim solution will probably give the most reliable results. When the vehicle traverses multiple borders at some point it becomes impossible to have a home-PLMN SIM from each country, making the multi-sim solution less scalable.

Learnings from the DE TS tests

The DE TS trials of the custom multi-SIM solution have been conducted in the urban setting in the city center of Berlin, with heavily overlapping coverage of Deutsche Telekom and O2 mobile networks. While the 5G NSA coverage of Deutsche Telekom fully covers the DE TS track, the 5G NSA coverage of O2 was limited to a part of the trial site. This characteristic of partial O2 5G coverage was exploited in the trials to set up a virtual border at the location that denotes the end of 5G NSA coverage. In the 5G-MOBIX trials we have therefore concentrated on trialling the implementation decision of a prediction function, i.e. switching the operator at the particular geographical location to avoid coverage issues (as to be expected in cross-border contexts). In contrast to network-controlled handovers, the custom multi-SIM solution employed by the DE TS puts the control of the connection into the vehicle application. For the platooning use case the DE TS solution involves a dedicated MQTT client for each modem, so that we aim at minimizing the mobility interruption time of receiving EDM messages from the eRSUs in the two service areas that lie on each side of the virtual border. As described above no tunneling service is used and the connection is broken in a controlled fashion (i.e. location) from UE perspective. It should be noted that the eRSU-assistance service and its V2X client application on the vehicle is state independent, so we can concentrate on minimizing interruption time without caring for session continuity on MQTT level. More complex stateful-applications require the appropriate handling on the respective network and application layers before breaking the connection. This make-before-break approach for state-dependent applications require more intelligence and control being placed into the OBU application, and the network-side support to minimize the impact of breaking the connection. The DE TS trials of the custom multi-SIM solution have shown the viability of utilizing the GPS position to implement mobile network switching decisions for applications that can tolerate reconnections.

3.5. Continuity measures

When a vehicle moves across different regions or even across different networks different continuity measures should be taken to keep the vehicle always connected to the best network services available. Different technologies will contribute to keeping the best connection available:

- Session and Service Continuity (SSC) (par 5.6.9 3GPP 23.501 [11])
- URSP Rules to configure the UE with the correct network information for a specific network service
- Local UPF to keep the traffic in a certain region (edge computing)
- Edge Application Server Discovery Function (EASDF) with an edge DNS edge client (EDC) as specified in 3GPP SA2

Edge enabler server (EES) with an edge enabler client (EEC) as specified in 3GPP SA6.Both studies (SA2 and SA6) describe different solutions to reach similar goals, although in some ways they can be complementary. Figure 16 (from a presentation[4] by the chair of SA2) compares both studies.

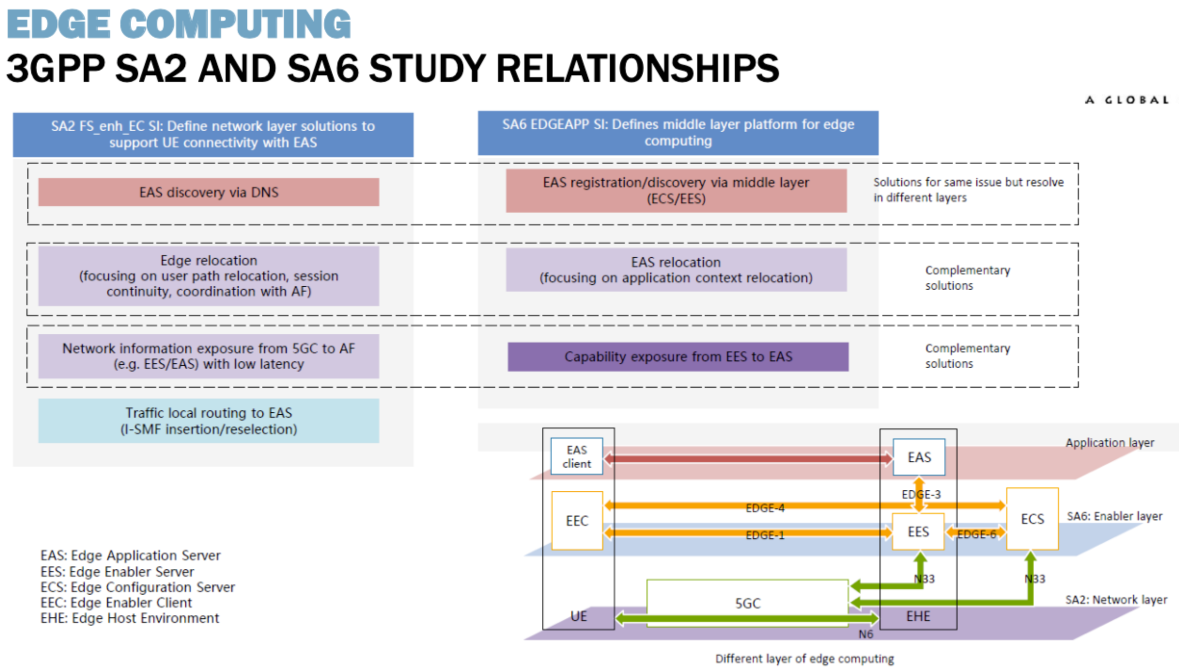


Figure 16: 3GPP SA2 and SA6 Study Relationship

Different technologies can work together or replace each other to enable service continuity. At the network layer, the UE connects to a data network where the application server resides. In order to have the application on the UE discover the correct application server and rediscover the application server after a network change, mechanisms are needed to control this. Within 3GPP different approaches exist to achieve this.

At the network layer, a local UPF can route the traffic to a local (or regional) data network where the application server exists. URSP rules can help configure the UE to route the traffic to the correct data

[4] Source from: https://global5g.org/sites/default/files/VerticalWebinar_SA2_update_Edge_Computing_PuneetJain.pdf, accessed Feb 26, 2022

network and slice. SSC mode 2 and 3 can keep the UE connected to the best data network, with minimal connection loss. To help the application at the UE side discover where the application server can be found, a DNS approach can be taken (similar as in SA2) or an edge enablement layer approach can be taken as defined in SA6. Altogether also another approach can be taken, defining an application function which helps steer the UE to the correct data network and discover the application server.

As it is currently, almost none of the above-mentioned technologies are available in today's networks and modems. What is possible with the latest network technology is:

- A local user plane function and data network to keep the traffic locally and lower the latency
- (Local) DNS to discover the application running in the data network

Within 5G MOBIX both the local user plane function and local DNS have been evaluated.

3.5.1. Standards

Within 3GPP 23.501 [11], the 5G network technologies have been specified including Session and Service Continuity measures to enable make before break (SSC mode 3) or break before make (SSC mode 2). The work done on SA2 within 3GPP has been specified in TS 23.548 [17] (SA25G System Enhancements for Edge Computing). The work on SA6 has been specified in TS 23.558 [18] (SA6 Architecture for enabling Edge Applications).

Another corelated solution is the ETSI solution [19], which uses enhanced DNS for service discovery. The ETSI solution is comprises of an edge computing platform with different interfaces and functions specified to enable functions like deployment of services, service discovery, data routing, etc.

3.5.2 Architecture

Within the 5G-Mobix project, a partial service discovery solution has been implemented and tested within the Finnish trial site. This solution compares to 3GPP SA2, using DNS to expose the IP address of a nearby service based on the domain name. However, the solution has been extended to allow for central management of all DNS records.

Each data network consists of at least an application server running at the MEC (Multi-Access Edge Computing) facility and a local DNS (LDNS). Upon connecting to a data network, the vehicle performs a DNS query to the LDNS to request the address of the application server. Each MEC registers itself by a global coordinator, responsible to keep a global configuration. Each LDNS operates as a relay in the network, relaying queries to the central DNS which is configured by the central coordinator. This architecture is depicted in Figure 17.

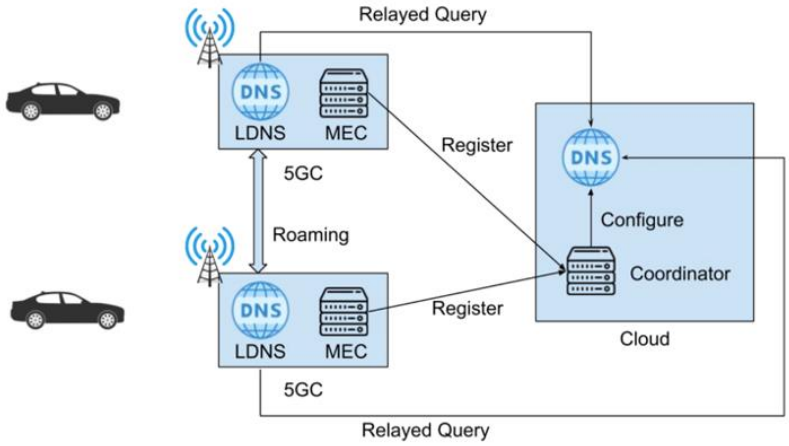


Figure 17: Architecture for Continuity Measures

1. Comparing with 3GPP SA2, the major differences with the solution tested in 5G-Mobix is the setup that relies on an existing DNS architecture for service discovery, instead of introducing new 5G core network functions. In 3GPP SA2, EASDF is proposed to handle DNS queries in the core network and EDC is proposed to direct DNS queries to the EASDF on the UE. In our solution, we use LDNS to handle DNS requests and the IP of the LDNS is notified to the UE during the DHCP IP assignment process implemented at the UPF.
2. We manage the UE-MEC mapping at the DNS architecture, instead of at the core network. In 3GPP SA2, the SMF is responsible for instructing the EASDF on handling DNS queries. In our solution, we keep this information at the cloud DNS authoritative server (along with the central coordinator) and all LDNS should forward the received DNS requests to the cloud DNS authoritative server for handling the requests.
3. We use LDNS to inject PCI information as an EDNS record to the client-generated DNS requests. 3GPP SA2 uses EASDF to inject DNS queries and uses client subnet information instead of PCI.

3.5.3 Learnings

We have tested the proposed architecture during the trials performed in the Finnish trial site in December 2021. The service discovery may not have been successful all the time. DNS is built on top of an unreliable transport layer protocol, UDP. So, a DNS query may not get any response if any of the intermediate packets is lost. We made 12 round trips on the testing road and found that DNS query failure happened in 4 of the rounds.

Service discovery latency is low on average, but with a significant number of packets having a larger latency causing a tail latency. The median value of the DNS query latency is 49.0 ms, which is close to the round trip time (RTT) that we observed between the UE and the core network. The value is a bit larger than the 10ms-level of RTT reported by other 5G measurements because the OBU in use has introduced additional delay. The longest DNS query delay observed during the trial is 356 ms. Regarding that the ethernet network is comparatively more reliable than the cellular network, we believe that the tail latency is majorly caused by the buffering, congestion, or bad signal strength in the cellular network.

The service discovery experiences some delay on detecting PLMN change. We detect the network change by monitoring the UE's public IP address, which is tested every 1 second. It means that the vehicle may spend up to 1 second to notice that it has changed the network. The problem also introduces additional delay in service migration. Such delay may be reduced if the interval of probing the public IP address is reduced but will impose more burden on the network.

Dynamic update of the edge server's address is not supported. We store the address of the edge servers in the cloud and the information is cached in the LDNS after the first query. When the record is updated in the cloud, the new record will be visible to the UE unless the cache expires in the LDNS. In this case, we must manually invalidate the cache in LDNS if we want to update the change in edge servers immediately, which is doable but not scalable.

Robust for both supported and unsupported UEs/LDNS. In the cloud DNS authoritative server, it stores a (PCI, IP address) map for each domain name. For each incoming DNS request, it follows three steps for name resolution. 1) If the PCI is provided in the DNS query's ECS, directly check the stored data, and respond. 2) If the PCI is not provided, use the DNS query's source IP address, along with IP geo-address dataset to guess the UE's PCI and respond. To the ECS, it may be provided by the UE on generating DNS query or be injected by the LDNS.

Impact for MNO: We use cloud coordinators to manage the availability of the edge servers to the clients. So, we expect that some third party, e.g., application service provider, can manage edge servers across mobile networks without the need of MNO.

Impact for OEM: Our solution relies mostly on the application layer protocol DNS and doesn't require change to the 5G core network. So, we do not see any impact on the OEM.

3.6. Slicing

Network slicing is the technology used to create multiple virtual networks within a given physical network. Slicing can serve different goals, an important goal in 5G-Mobix is the tailoring and guaranteeing of QoS and capacity for specific groups of services. Network slices can extend across both the RAN and the core network to provide an end-to-end virtual network.

3.6.1. Standards

Network slicing has been specified in 3GPP in various normative documents both on the requirement level (3GPP TS 22.261) [10], on the architecture level (TS 23.501) [11], procedure level (TS23.502) [12] and at the management level (TS 28.530) [13]. The 5G-Mobix use of slicing technology follows these and other 3GPP standards. The standards are complete and sufficient for our purposes. Our challenges proved to be in the availability of the implementation network functions and UEs that implement the standards.

3.6.2. Architecture

The slices in both core and RAN are identified by slice IDs: the Single Network Slice Selection Assistance Information (S-NSSAI) = Slice Service Type (SST) + Slice Differentiator (SD)). They are communicated from the UE to the network during each PDU session setup. After that, the network will map the slice IDs to specific QoS guarantees by using the Network Slice Selection Function (NSSF). Figure 18 shows a local-breakout slicing setup which is an example architecture from our trials.

The slices used in 5G-MOBIX extend across RAN and core. In the core, this means, among other things, that each slice has its own UPF in the data plane and its own SMF in the control plane. As the capacity in the core is dimensioned to be abundant, there are no measures for prioritizing between slices or guaranteeing capacity. The different slices are isolated from one another, as they should be according to the standards. In the RAN, capacities can be limited. Therefore, the S-NSSAIs that identify the different slices are mapped to priorities in the radio network. The precise implementation and effect of the slice priorities in the RAN are vendor proprietary. It is possible to give a slice an absolute priority over other slices, implying that the other slices will only receive radio resources after the demand of the priority slice has been met. Another general option is to give relative priorities, implying that in case of lack of resources or capacity, the available resources are distributed over the slices according to some predefined ratio. The mapping of the S-NSSAI values signaled by the UE during PDU session setup to the priorities is done in the gNb.

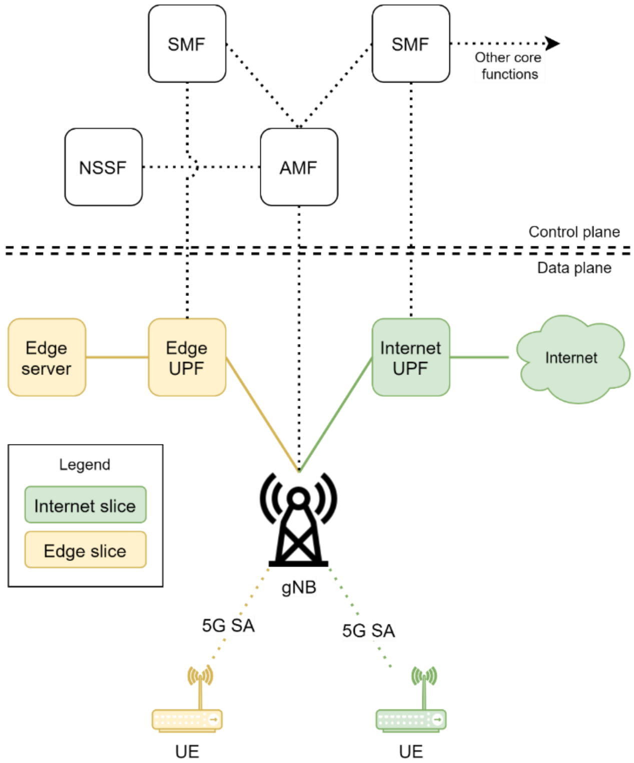


Figure 18: Slicing in RAN and core network in combination with local breakout and edge computing

3.6.3. Learnings

The detailed numerical results of our tests will be described in deliverable D5.2 [20]. Overall, the tests show that slicing across RAN and core can be implemented and made to work. The prioritization of V2X traffic in the RAN has been successfully demonstrated. A point of attention is the UE behavior. In our tests, the expected priorities for the V2X traffic could only be achieved if the V2X and the regular internet traffic originated from separate UEs. If a single UE was used as a source for both V2X and Internet traffic, the expected priorities could not be observed, probably because there is a non-standard and unexpected dependence on the traffic in the slices internally in the UE.

Impact for MNO: We demonstrate that slicing works and can be effectively used to guarantee the connectivity for V2X traffic and applications during congestion. The configuration can be scaled up to (much) more than two slices. However, the dimensioning and the distribution of the capacities between the slices serving different groups of application and users through absolute and relative priorities will become complex.

Impact for OEM: The key point is that it is possible to guarantee the connectivity for V2X applications and through that the performance of the V2X applications, also in challenging situations with network congestions and suboptimal coverage. Still, in situations where the network coverage becomes too poor, the performance will degrade, also with slicing.

3.7. Predictive QoS

Predictive QoS is a solution which predicts the quality of communication based on collected information obtained from users, infrastructure, and network, and informs the predicted quality to the user so that user can adapt its behaviour such as application data rate or velocity etc.

3.7.1. Standards

The 3GPP is specifying Network Data Analytics Function (NWDAF) in the 3GPP TS 23.503 [21] and TS 29.520 [22] technical specifications that are closely related to the QoS prediction. The NWDAF collects information from other entities particularly from other network functions, and provides ML-based analytics such as:

- UE base analytics such as UE abnormal behaviour/anomaly detection and UE Mobility-related information and prediction, and UE Communication pattern prediction.
- QoS and QoE related analytics, including service experience computation and prediction for an application/UE group and Quality of service (QoS) sustainability involves reporting and predicting QoS change
- Load (system state) based analytics including various computation and network load data and their related predictions for different entities of the system such as Servers resources load, Network Function resources usage.

Because the specification of the NWDAF started lately, the FR TS has developed a QoS prediction module (an early version of NWDAF) that sits MEC, collects logs and predicts communication quality. Furthermore, FR TS has specified an IQN (In-Advance QoS Notification) message that will be used by the QoS prediction module to inform the users of the predicted quality.

3.7.2. Architecture

Figure 19 describes the architecture of the QoS prediction solution developed at the FR TS. The key entity of the predictive QoS is the “Predictive QoS Module” that collects data from the vehicles, infrastructure and the network, predicts the quality, and notifies the predicted quality to the users. When notified with a predicted QoS, a vehicle may adapt the data rate of applications or the vehicle parameters, such as velocity.

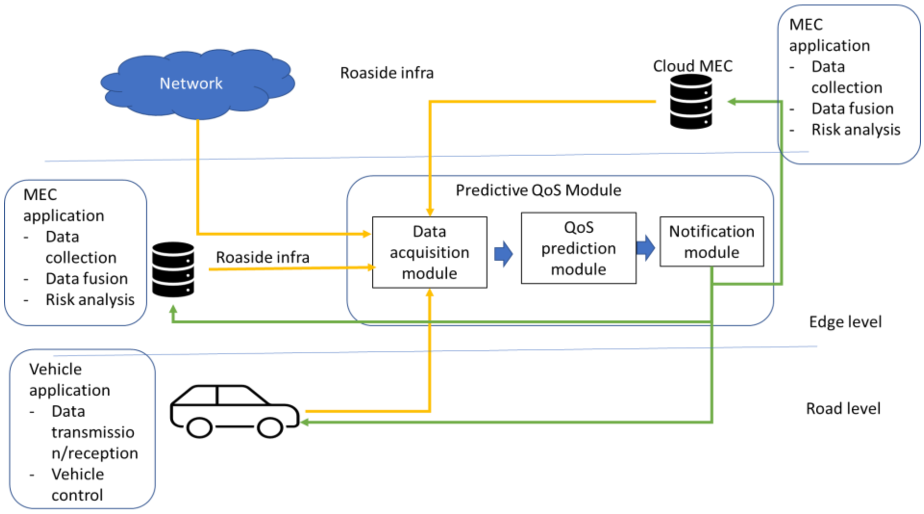


Figure 19: QoS prediction solution

A large number of KPI parameters of level 0 (RSRP, SINR etc.), level 1 (throughput, delay, packet loss etc.), cell information, and vehicle information (position, velocity etc.) have been collected at the predictive QoS module which applies random forest ML and predicts basically throughput. The predicted near future throughput is notified to the vehicle, via IQN message depicted in Figure 19.

Table 25: IQN message format

Element	Value	Description
Header		
Destination Port #		Destination vehicle/end user port number
Src Port #		Source Predictive QoS centre port number
Destination IP address		Destination vehicle/end user IP add
Src IP address		Source Predictive QoS centre IP address
Payload		
Action ID	INT	0 : unknown 1 : data rate 2 : speed 3 : XXX
Action Element	INT	0 : unknown 1 : application Id 2 : vehicle control unit 3: XXX
Action Value MIN	Min Double	If Action ID= 1 {min data rate in bps) If Action ID = 2 {min speed in m/s)
Action value MAX	MAX double	If Action ID= 1 {max data rate in bps) If Action ID = 2 {max speed in m/s)
Action start time	time	Start time of the action
Actional end time	time	End time of the action
Action ID	INT	0 : unknown

		1 : data rate 2 : speed 3 : XXX
Action Element	INT	0 : unkown 1 : application ID 2 : vehicle control unit 3: XXX
Action Value MIN	Min Double	If Action ID= 1 {min data rate in bps) If Action ID = 2 {min speed in m/s)
Action value MAX	MAX double	If Action ID= 1 {max data rate in bps) If Action ID = 2 {max speed in m/s)
Action start time	time	Start time of the action
Actional end time	time	End time of the action

Upon reception of a IQN message, the vehicle adapts application data rate. The FR TS has developed an application, which can fine-tune its data rate, dedicated to the tests of QoS prediction.

3.7.3. Learnings

First logs collected by FR TS and fed to the ML model were based on an early version of the 5G SIMCOM modem which was able to collect only few data. Then, it became clear that the model cannot be sufficient to perfectly fit for usage of OBUs with other modem (with improved antenna performance) as well as smartphones. To solve the issues, more data have been collected to improve the performance of the QoS prediction and learn model which can be adapted to different receivers.

Second, QoS prediction is dependent on the resolution of collected data, so, tools used for collecting data on radio performances have been upgraded to provide data more frequently and to geolocalise radio measurements. In that way, radio map on the experimentation area have been obtained at a high resolution to enable a fine adaptation of QoS prediction.

Third, the current solution is largely based on the data obtained from UEs. Indeed, while experimental networks can provide data such as cell occupancy, the logs under experimental network do now show much variation (due to very few UEs using the network). Once MNOs work on the solutions under active networks, they should be able to have richer information and get better QoS prediction. QoS prediction is an extremely interesting solution for OEMs, particularly for automated driving applications.

3.8. Satellite fall-back

Service continuity is a key requirement of the CAM applications. Low network coverage (or coverage gap) is one of the situations where ensuring service continuity becomes challenging. Due to its global coverage, using satellite communication in such scenarios, i.e., satellite fall-back, can be an attractive solution, especially for use cases that don't require extremely low latencies and/or vehicles that could sustain the additional cost of a satellite module (e.g., trucks).

3.8.1. Standards

Activities inside the 3GPP RAN and System Aspects Technical Specification Groups (TSGs) on NTN started in 2017 under Release 15 and are still ongoing. The work of 3GPP RAN study groups on NTN NR was completed in December 2019, and the normative work started in August 2020 in Release 17. NTN IoT became a work item as of 3GPP Release 17. The work in SA groups depends on the progress of the RAN groups and may proceed further after the normative work in RAN reaches a certain level.

Table 26 lists all features and study items on NTN investigated by the 3GPP from Release 15 to Release 17. In particular, a certain 3GPP feature or study item is associated with a lead body (i.e., R for RAN aspects and S for system aspects) and the completion field indicates when the 3GPP feature or study item was completed or is expected to be completed.

Table 26: Feature List for Satellite Fall-Back

Release	Lead Body	Feature and Study Item	Completion	Technical Report
15	R1	Study on NR to support Non Terrestrial Networks	2020-10-08	TR 38.811
16	R3	Study on solutions for NR to support Non Terrestrial Network	2021-06-30	TR 38.821
	S1	Integration of satellite access in 5G	2018-09-14	n/a
17	S2	Study on architecture aspects for using satellite access in 5G	2021-03-31	TR 23.737
	S5	Study on management and orchestration aspects with integrated satellite components in a 5G network	2021-04-06	TR 28.808
	R1	Study on NB IoT/eMTC support for Non-Terrestrial Networks	2021-06-30	TR 36.763
	S2	Integration of satellite components in the 5G architecture	2022-03-11	n/a
	R2	Solutions for NR to support Non-Terrestrial Networks	Expected 2022-09-12	n/a

3.8.2 Architecture

One of the main characteristics targeted by satellite is service continuity by offering global coverage. To support this functionality, the OBU in the French trial site has access to both terrestrial and non-terrestrial radio bearers through an intelligent routing device. The routing engine automatically determines the most appropriate bearer based on signal strength, communications statistics, connectivity predictions and preferred mode of connectivity. For instance, this would mean using the satellite bearer for critical traffic whenever the terrestrial 5G NR is unable to satisfy the connectivity requirement (e.g., due to unavailability, signal degradation, etc). Figure 20 illustrates the end-to-end hybrid 5G-satellite architecture that is deployed.

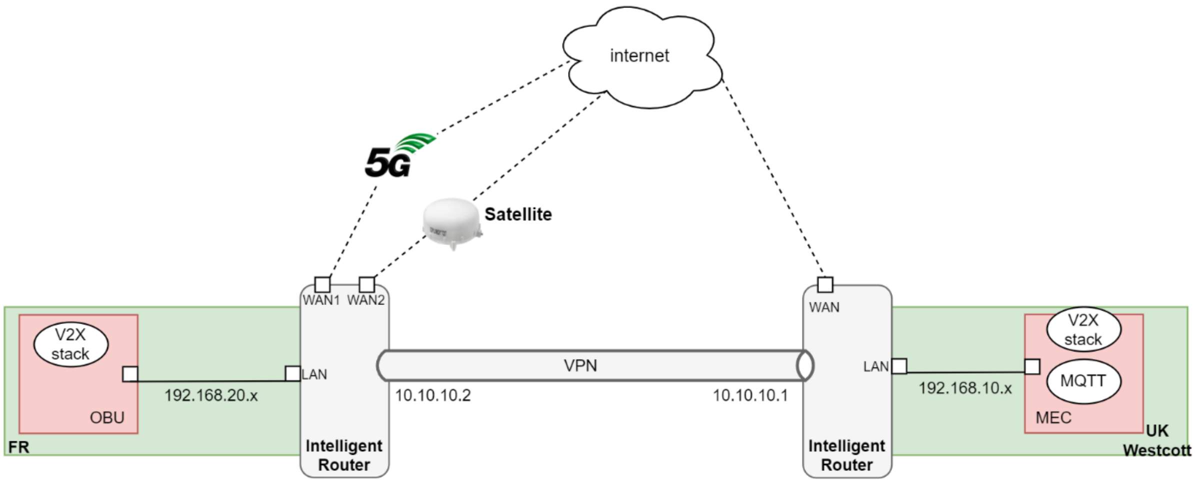


Figure 20: Hybrid 5G-satellite intelligent routing-based deployment at the French test site

As mentioned before, due to ongoing standardization, actual 3GPP NTN does not yet exist, the trial site therefore uses the available technologies to create the result and learnings that will feed back into standardization and the knowledge and service offerings of the French Trial site partners.

As shown in Figure 20, a Commercial-off-the-Shelf (COTS) routing device equipped with mode switching and RAT bonding capabilities, is integrated with the OBU. The OBU is connected through the router's LAN interface and the router is configured with two wide area network (WAN) interfaces, one dedicated to terrestrial 5G connectivity and another to satellite Low Earth Orbit (LEO) connectivity. The part of satellite connectivity is attained by using the LEO land-mobile Thales Mission Link terminal. The terminal can be easily deployed on the vehicle and it contains an electronically steerable phased array antenna, capable of tracking the Iridium Certus LEO satellite constellation. Based on the availability of satellites, the terminal can provide speeds from 180 up to 700 Kbps.

3.8.2. Learnings

According to the tests which have been performed satellite communication should be used in a back-up solution when terrestrial 5G technology is not available. Indeed, with satellite higher latency some packets loss have been experienced. Thus, this solution is suited to maintain a link with the vehicle for specific applications, e.g. to continue tracking its location and transmit specific events.

Besides, this requires specific hardware (antennas and modem) to be mounted on the vehicle. Depending on the configuration, e.g., open sky or presence of buildings, satellite coverage can influence performances of this system. In a first stage, open sky conditions were expected to result in the best outcomes for highway cross border sites.

Finally, as satellite fall-back has been tested in a hybrid architecture with 5G terrestrial connectivity, it has been shown to be able to maintain connectivity with a VPN server to be integrated in such an approach which combines multiple technologies.

3.9. Local break-out roaming, compared to Home routed roaming

Most of the current roaming architectures are using home routed roaming. All the data traffic is routed back to the home operator. The further away the user is from the home network, the higher the latency of data traffic. To overcome this, local breakout architectures can be used. The data traffic stays with the visited network.

3.9.1. Standards

Within 3GPP TS 23.501 [11] the different architectures are described. In addition, GSMA IR.88 [23] describes the EPS roaming guidelines, agreed between operators.

3.9.2. Architecture

In the home routed architecture (see Figure 21), the PDN gateway resides in the home network. The data traverses over the regular roaming interface between operators using the GRX/IPX connection (a common interface between service providers used for roaming data). This interface connects different roaming operators and is not necessarily optimized for low latency. In 3GPP TS 23.501 [11], the different roaming architectures are described. In addition, the GSMA describes the roaming agreements regarding the 5G Core in NG.113 v5.0 GS Roaming Guidelines [24].

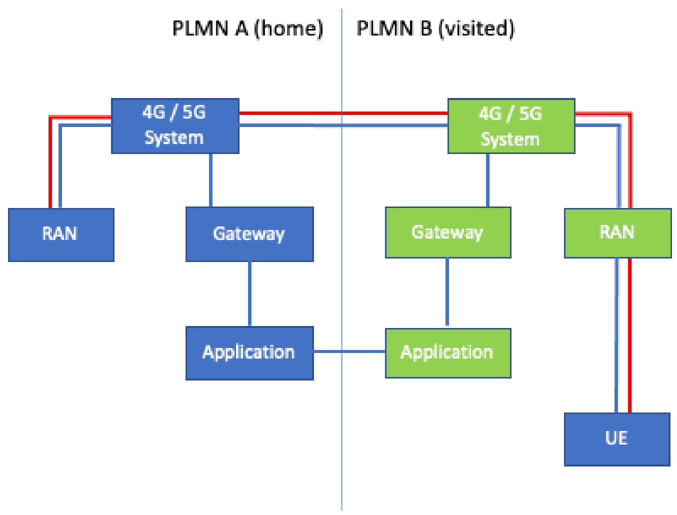


Figure 21: Local breakout and application

Figure 21 depicts a generic architecture of a 4G or 5G system interacting with a UE and application server. Each PLMN has its own gateway connecting the mobile core to the internet, PLMN services or private networks. To have benefit of a local breakout architecture, the application to which the UE will connect must be present close to the gateway. Also, if for instance the application helps vehicles to interact with each other, it stands for reason that a connection is needed between the application servers at the different PLMN's.

3.9.3. Learnings

LBO functionality is tested at both the GR-TR and ES-PT cross border corridors. The visited MME will be configured to select the visited PGW for certain IMSI's and a specific APN. In the MME the APN Local Breakout Control function will be used. These trials took place using a 4G NSA system. Since both cross border corridors have implemented a handover, the question arises when to switch to the local network. During a handover the data session is kept alive without interruption. To connect to the local network, using the local breakout architecture, an interruption is needed. The network is configured to connect the UE to the local network when a new data session is established. In order to establish a new data session, the existing data session to the home network needs to be gracefully disconnected. There are two ways to trigger a disconnect of the home routed data session:

- Triggered by the network, e.g. on a tracking area update
- Triggered by the UE when the local situation allows this

If we would have the network trigger the disconnect, this would have happened directly following the handover. This would then negate the benefit of having a handover in place and possibly happen at the wrong moment (e.g. when the vehicle is relying on the network). This leaves the trigger by the UE. For this the UE needs to select a moment in time to gracefully disconnect the data session after which setting up a new data session immediately.

Above difficulty can be overcome with the 5G Core system, implementing SSC mode 3. This way the network can trigger a new data session without the application losing the old connection (make before break). This functionality is however not available for testing with current networks and UE's. Besides setting up a new data session, the application still needs to be triggered to connect to the closest network application. More on this can be found in section 3.5.

From an MNO perspective, there are still some difficulties to allow for a local breakout at a visited PLMN. Metering for instance, takes place at the PGW. A home PLMN would need to trust the visited PLMN to provide correct metering data and be able to audit the correctness of the data. Also, operators are required to facilitate the legal interception of data if requested by the government. There are no EU processes in place to facilitate the legal interception of data cross borders.

It is expected that there are different types of connections needed to facilitate the applications running in a vehicle. Some applications might need regular internet traffic, others might need voice services and yet others local messages with a low latency. It is unclear if all these applications can be serviced with a single APN or data network. It is expected that a more complex architecture is needed to facilitate this. The vehicle would need to be aware of different APN's or data networks to use, be able to selectively route traffic and have the required hardware to enable these requirements.

3.10. Comparing internet based with direct connect peering between operators

Current PLMNs use the GRX/IPX network to interconnect with other PLMNs. Different hops might exist between PLMNs and the connection is not always optimized to give the lowest possible latency. Future requirements thus will ask for lower latency connections between operators. The most important reasons for this being:

1) With seamless handovers between PLMNs using the S10 interface, signalling will take place while doing a handover. The source gNB will signal the target gNB and messages go back and forward several times. Larger latencies will cause delayed handovers. Depending on local conditions this might give undesired results if the handover windows is short.

2) The S8 interface being in the data path between Visited SGW and Home PGW would take advantage from the shortest delays achieved by the direct interconnection, minimizing the E2E delay for applications.

The applications supporting the vehicles need to keep the same state. If a vehicle needs to reconnect to the new application across the border it will need to keep working and use information from vehicles (still) connected to the other PLMN. A direct connection between the applications supporting the local vehicles will help to keep a current state.

3.10.1. Standards

Within IR.34 [25] from the GSMA, guidelines are given for IPX provider networks. Direct connections between PLMNs using leased lines are not part of these guidelines however.

3.10.2. Architecture

The IPX architecture is described in IR.34 and included below in Figure 22.

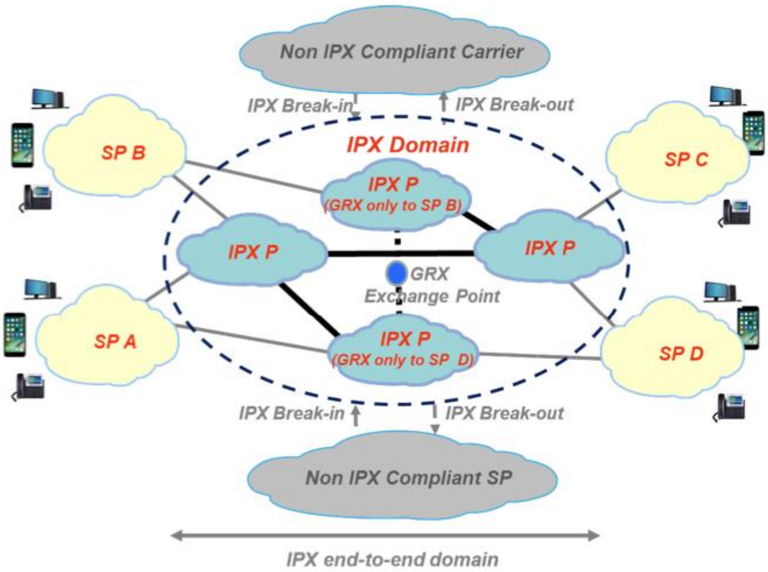


Figure 22: IPX model from GSMA spec IP.34

Different IPX connectivity options exist:

- IPX Transport (bilateral agreement between two Service Providers using the IPX transport layer)
- IPX Service transit (A bilateral agreement between two Service Providers using an IPX Proxy functions and the IPX transport layer)
- IP service hub (using a single agreement to reach multiple Service Providers)

3.10.3. Learnings

Within ES-PT, a direct connection has been established between NOS and Telefonica, preventing the need to route traffic through the main core network using a central but distant location in both countries to interconnect both PLMNs. The main benefit is that traffic is kept in the same region. If the direct interconnect would have been made on a central level, the benefit would have been relatively small compared to the existing IPX interconnect. The main benefit of creating a local interconnect is to keep the latency low when a handover takes place to the other country. However, when the vehicle moves further into the country other measures are needed to keep to latency low, like for instance a local breakout.

Measurements at the Spain – Portugal border show a round-trip time of 17 milliseconds using the direct connection. When using an internerconnect over Internet the round-trip time is 48 milliseconds. The 30 milliseconds of difference are due to increased distance because of typically centralized internet exchanges.

In case of the GR-TR trial a direct connection has been established between the two edge sites Alxandroupoli and Kartal, allowing both network related (e.g. S6, S10, S8, interfaces), as well as application related signalling and traffic to enjoy shortest delays (in the range of 45-50 ms) compared to an of internet based interconnection, which is a significant gain for delay sensitive applications.

For home routed scenario though such a benefit would be diminishing in significance as the distance between the visited edge and home edge increases as the truck moves away from the border in his path within the visited country. Further the question as discussed above about the scalability would remain. In case of local break-out the benefit of meshed interconnection between edge sites would not provide significant gain related to shortest signalling and data paths.

The benefit for a local interconnect is large when also using a handover. The latency is kept low and the applications in the vehicles can keep the low latency connection as required during the handover. For the MNO however this may have a large impact. Currently most operator networks have designed with a mind for availability, using load balancing technologies to route traffic between regions to keep the highest availability possible. A complete redesign might be needed by the MNO to allow for this regional approach with local interconnects across the borders.

3.11. Angular domain positioning using mmWave

Augmenting positioning 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, this can improve localization accuracy beyond the accuracy available from GNSS-type positioning even when only few reference stations are available. 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.

3.11.1. Standards

As a basis for the mmWave based localization, 3GPP TS38.305 [26] was evaluated, where the positioning based on compressed sensing and angular domain information can be regarded as a UE-based DL positioning method, combining information that would be used in DL-AoD and DL-TDOA of Table 4.3.1-1 of TS38.305 with additional information available at the UE (DL-AoA).

The proposed localization methods go beyond TS38.305 [26] in including DL-AoA information and employing compressed sensing techniques to identify relevant transmission path contributions and derive the positioning estimate from the estimated channel and available DL-AoD and DL-AoA information, with focus on cases using realistic mmWave antenna arrays and analogue beamforming. Similarly, the information that may be provided to the UE via the LMF is extended to be a superset over those specified in the relevant clauses of TS38.305 (8.11 & 8.12) [26], while for the simulations and tests the signalling is simplified to allow focus on localization performance.

As basis for the tests and simulations conducted, the 5G NR Physical Layer specifications from TS 38.201 [27] and TS38.202 [28] were considered. At the same time, in simulations and tests, many of the higher layer functions were simplified or omitted where they were evaluated to not impact localization performance.

3.11.2. Architecture

The general setup and architecture for the mmWave 5G signal based localization is shown in Figure 23, where an end-user (UE, here the connected/autonomous vehicle) aims to derive its position relative to one or multiple antenna sites/base stations (BSs) based on the DL signals received from these base stations. To perform localization, the UE regards the received DL signals and respective estimated channel in combination with the known DL angle of arrival (AoA) at the UE as well as angle of departure (AoD) from the BS(s).

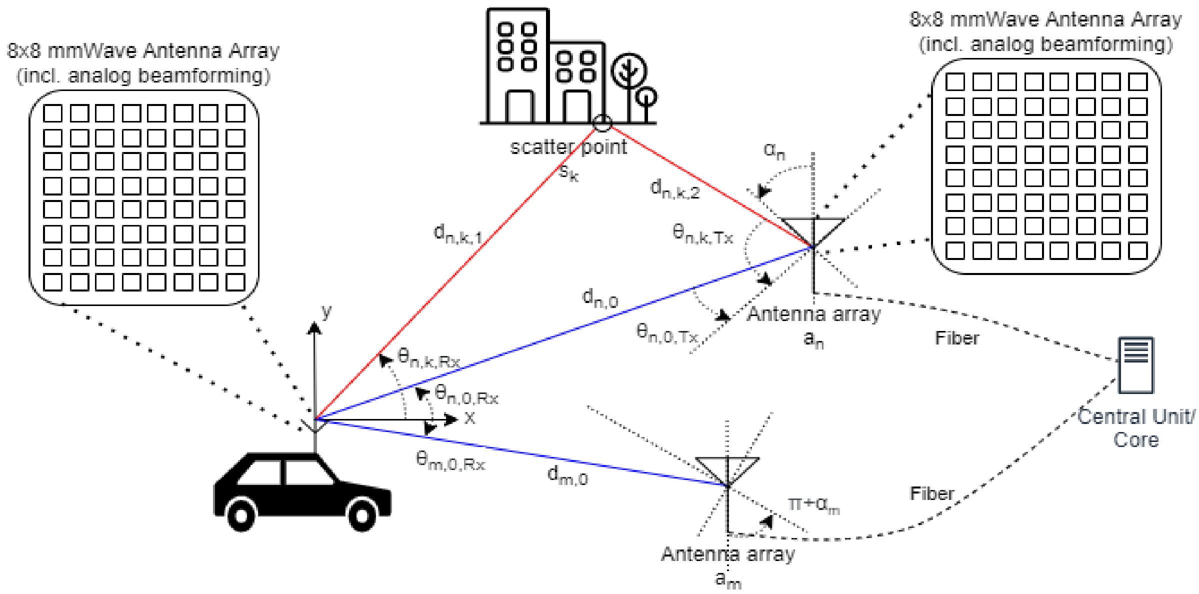


Figure 23: Architecture and setup schematic for precise positioning using compressed sensing and angular information form 5G mmWave signals

3.11.3. Learnings

Early simulation tests suggest capabilities of 0,3 m positioning accuracy with realistic mmWave signal conditions and Tx/Rx antenna array sizes. It should be noted that a significant dependence of the localization performance on the granularity of the beamforming or the angular resolution of the estimation of AoD/AoA is observed. Furthermore, dependence on signal bandwidth is expected to be small, when operating at signal bandwidths of 100 MHz or above.

The system relies on similar processes as DL-TDOA and DL-AoD/AoA from 3GPP TS 38.305 [26] for localisation/positioning. However, our implementation does not fully consider application level, but more network level; The processing for localisation is mainly executed on vehicle OBU, taking into account information about beam angles (which need to be made available by gNB) and about precise position of the gNB (which can be provided over-the-top by LMF running in edge or cloud). Our implementation does not fully consider application-level implementation on an MNO edge cloud. If MNO cloud or edge is incorporated, it would require implementation of an augmented LMF providing information on precise locations of the gNB/antenna arrays and the user-specific DL-AoD. No further network impact above those considered in TS38.305 [26] is expected from such an implementation, provided sufficient angular resolution is achieved during standard beam alignment/acquisition processes.

Processing of the localisation is taking place on the vehicle, requiring significant processing power and direct access to raw channel state estimation data or raw signals from the 5G modem. Further augmentation of localization precision or fusion with other sources of localization data are expects to reduce the error/margin of localization and to improve redundancy. This would require an OBU, that is connected to the CAN-bus in order to retrieve vehicle speed information. Other than that, it is self-supporting, but would require an interface to fuse the position of the original GNSS signal (assuming in an L4 vehicle this is always provided using an DGPS system), in order to retrieve the positioning via 5G as a backup.

3.12. mmWave for CAM

Following is a list of key enablers essential for an mmWave 5G NR communication system to provide broadband and reliable link performance for two Uss, Tethering via Vehicle (US 5.2) and Remote Driving (US 4.5). Remote driving uses a relatively large portion of the uplink bandwidth in current mobile networks. mmWave can provide the extra spectrum needed but will be difficult to deploy next to roads because of the short range and high path loss when penetrating objects or reflecting from objects.

3.12.1. Standards

To support high mobility in mmWave bands, the following key enablers have been specified in the 3GPP 5G NR specifications (3GPP TS 38.211 [29], 3GPP TS 38.212 [30], 3GPP TS 38.213 [31], 3GPP TS 38.214 [32]) and implemented on the KR-side mmWave-band vehicular communication system:

- Flexible numerology with scalable subcarrier spacing to adapt to various frequency band configurations.

- Dense DM-RS allocation in the time domain allocation for improving channel estimation performance in high-mobility scenarios.

However, the following enabler is not supported in the current 5G NR specifications:

- A handover procedure dedicated for unidirectional antenna networks.

3.12.2. Architecture

The network architecture of an mmWave vehicular communication system for supporting two Uss, Tethering via Vehicle and Remote Driving, is illustrated in Figure 24. A gNB consists of one or multiple central units (Cus) and one or multiple distributed units (Dus) deployed along the roadside, and MAC-PHY functional split is adopted so that Cus are responsible for the processing of higher-layer protocols and Dus are involved in the processing of physical layer and RF. Optical fibre is used for the fronthaul connectivity between Cus and Dus, and each CU is further connected to the 5G core network that is also interconnected with the public Internet network and a remote driving platform located in a remote driving centre.

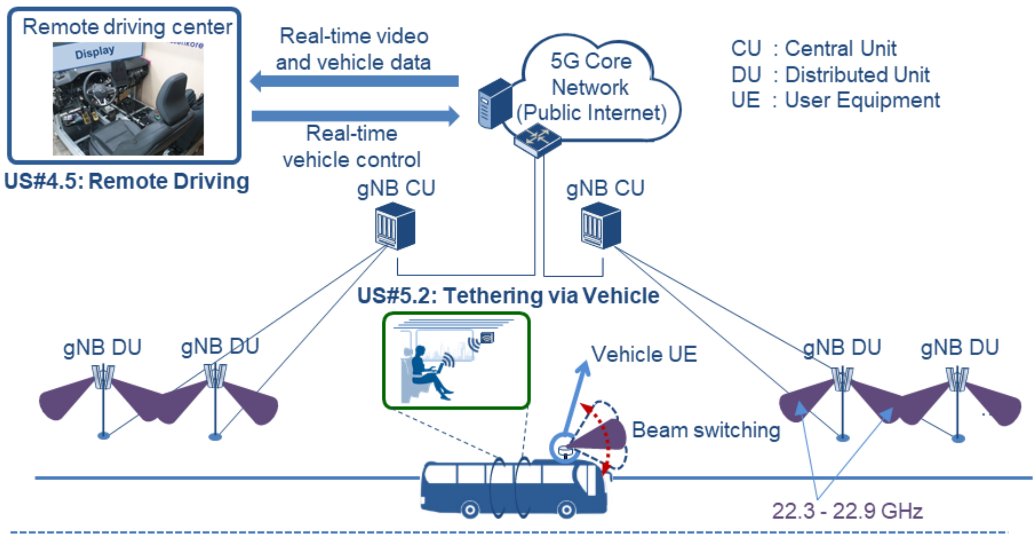


Figure 24: Network architecture

To prevent handover failures with mmWave, the A4 event is used to trigger the preparation of a handover. The A4 event is triggered when the RSRP of the target gNB is higher than a predefined threshold as seen in **Error! Reference source not found.**. If the A4 event is notified by the vehicle UE to the serving gNB, a h andover preparation operation is started (earlier than the conventional handover schemes using only the A3 event to trigger the procedure), thereby avoiding the handover failure situation.

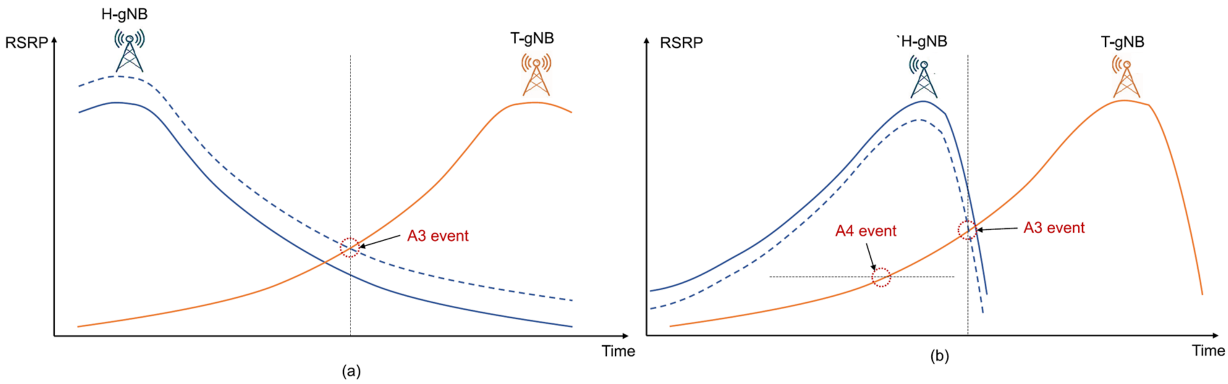


Figure 25: RSRP distribution during handover: a) Conventional omni- or bi-directional gNodeB deployment; b) Uni-directional gNodeB deployment

3.12.3. Learnings

Our field tests for two USs, Tethering via Vehicle and Remote Driving, were successful in the sense that key functionalities such as beam switching and handover were validated and performance requirements of the USs 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.

Impact for MNO: To address the two challenges, it is necessary for an MNO to thoroughly investigate and analyze 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.

Impact for OEM: Regarding the lessons learned from the test, no specific impact for OEM has been identified.

4. ES-PT CBC DEVELOPMENT, INTEGRATION & ROLL-OUT

4.1. Site Overview (CTAG-NOKIA)

The ES-PT CBC is one of the two cross-border corridors in 5G-MOBIX project. It covers the way between the city of Vigo (in the north-west of Spain), and the city of Porto (in the north of Portugal). Along this corridor, two 5G NSA networks have been deployed by different partners, with several nodes providing coverage to different areas. Four of these areas have been selected for testing the 7 CAM user stories (US#1.1.a, US#1.1.b, US#1.5, US#3.1.a, US#3.1.b, US#4.1, US#5.1) defined by the ES-PT partners, where different vehicles (autonomous, connected and legacy ones) cooperate with infrastructure taking advantage of 5G capabilities for testing complex manoeuvres and services.

The border between Spain and Portugal in the corridor areas is naturally divided by the Minho river and linked by several cross-border bridges. It is on two of these bridges, those linking the cities of Tui and Valença in the urban area (Old Bridge) and in the interurban area (New Bridge E01), where 5G tests are taking place in order to analyse their possible impact on autonomous and connected vehicle functions. The RAN deployment provides coverage not only on these two bridges, it also provides coverage at other important points along the Vigo-Porto route, where the agnostic and also use case specific tests were carried out. Tests have been carried out in a total of 7 locations included in the ES/PT cross border corridor:

- In CTAG's test tracks.
- A-55 national motorway in Spanish side.
- A-28 national motorway in Portuguese side that connects Viana do Castelo with Porto.
- New Bridge (International Bridge E01) Spanish side.
- New bridge (International Bridge E01) Portuguese side.
- Old Bridge Spanish side.
- Old Bridge Portuguese side.

The deployment by TELEFONICA is shared with commercial network (Spanish nodes work under PLMN 21438), while the NOS deployment is a dedicated infrastructure to the 5G-MOBIX experimentation (Portuguese nodes work under PLMN 26893). Figure 26 shows an overview of the Telefonica and NOS complementary network architectures.

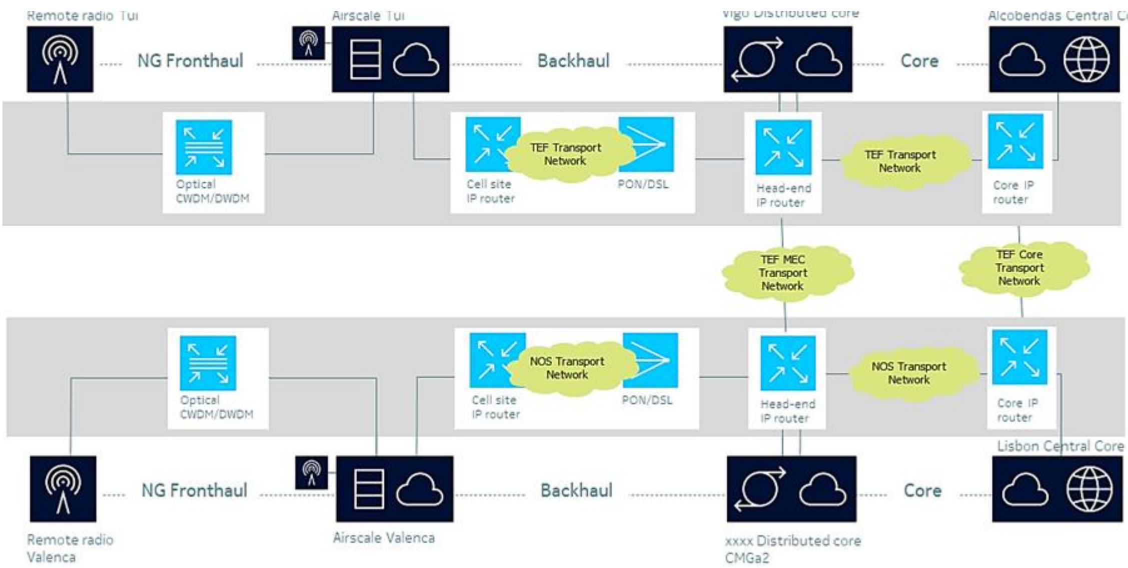


Figure 26: Telefónica & NOS Network architecture

This is the Release with redirect with S10 interface and home routed traffic implementation. Both core networks are interconnected through two transport networks, one connecting Central Cores and another connecting Distributed Cores. S6 interface is used to validate IMSIs from visiting vehicles and S10 interfaces is used to transfer the context information between the source and destination core.

The distributed core interconnection implemented is supported by a dedicated fibre between the NOS premises and the TELEFONICA premises. This dedicated fibre line provided by TELEFONICA is critical to understand the efficiency of the handover operation in the project. Not using dedicated fibre between operators implies using Peering mechanisms between Internet operators in different countries, which will mandatorily imply very high latencies (more than 30 additional milliseconds RTT between Spain and Portugal in this border) in the messages interchanged between vehicles and network.

Madrid to Lisbon distance is 628 km, while Madrid to Barcelona is 621 km, so distance is very similar. The average ping Madrid to Lisbon is around 48 ms while the average ping Madrid to Barcelona is 8 ms. As we can see for instance in "The WonderNetwork Global" Ping Statistics data is generated with the Where's It Up API, executing 30 pings from source (lefthand column) to destination (table header), displaying the average. This latency server is available in https://wondernetwork.com/pings. The following pictures provides real latency between countries using internet access:

	Barcelona	Lisbon
Amsterdam	31.884ms	43.963ms
Copenhagen	39.143ms	53.778ms
Frankfurt	23.978ms	45.357ms
London	27.945ms	48.08ms
Madrid	8.934ms	48.32ms
Paris	22.701ms	43.859ms
Stockholm	51.441ms	60.239ms
Tokyo	213.339ms	248.105ms

Figure 27: Ping times between WonderNetwork servers in several countries through Internet

In 5G-MOBIX we are using a direct fibre connection between Spain and Portugal that reduces the latency from Madrid to Lisbon to an average of 17 ms, compared to the average of 48 ms using Internet. In this particular case we observe an improvement in the Round Trip Time messages of 30 ms.

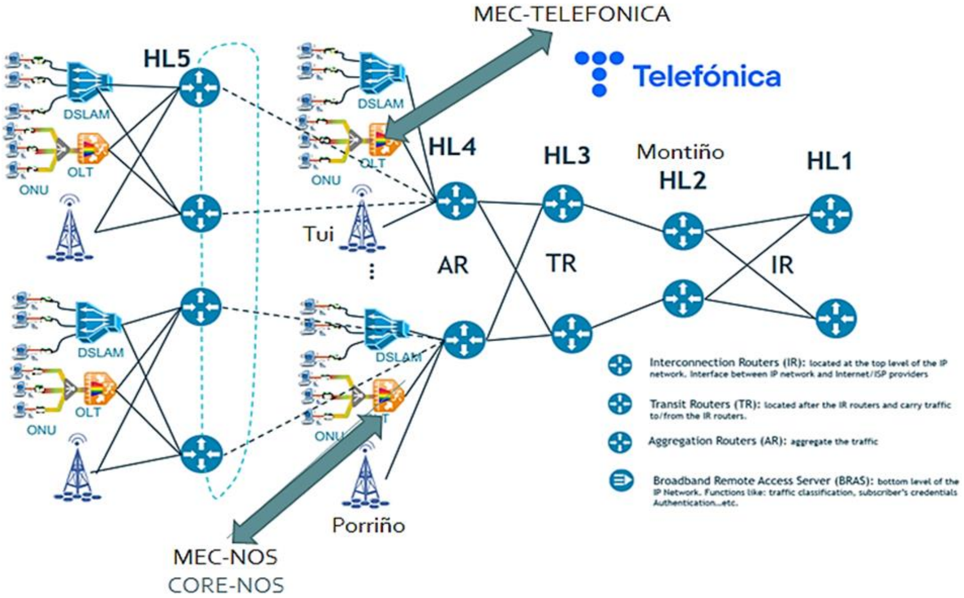


Figure 28: Distributed Cores and MECs Interconnection

In Figure 28, we can see how we have interconnected the Distributed Cores and MECs using a dedicated fibre line between the two operators. Packets between the SGW and PGW of both operators are transported by this fibre line, saving precious time for efficient V2X message interchanges between both operators.

In Internet peering interconnections the packets are sent to HL1 routers that are very centralized in Telecommunications operators and this implies more kilometres of fibre lines and more routers hops that takes more time.

To control the handover process we decided to use 3GPP A1, A2 and A5 events. Events A1, A2 and A5 are based on RSRP (power measurements of connected radios or neighbour radios) messages. The criteria for triggering and subsequently cancelling each event are evaluated after layer-3 filtering has been applied. The criteria for each event must be satisfied during at least the time to trigger. A1 and A2 activates the UE measurements, while A5 is used to configure the minimum RSRP on the actual radio network and the minimum RSRP on the neighbour radio network to start the radio handover event to the Network Cores.

TS 36.331 [15] Section 6.3.5 describes the message sent from the gNB to the UE (Measurement information elements) to advice it to measure a certain cell (in this case from a different PLMN) and report the measurement when certain conditions, that can also be configured, are fulfilled. The most Inter-Freq (IF) measurement thresholds used in NSA deployments could make use of the following standardized thresholds:

- A2 threshold (RSRP, RSRQ) – activates IF A3/A5 measurements
- A1 (RSRP, RSRQ) - deactivates IF A2/A3/A5 measurements
- A5 (RSRP) - IF Coverage measurements.

In Figure 29, we can see how the A5 event is configured:

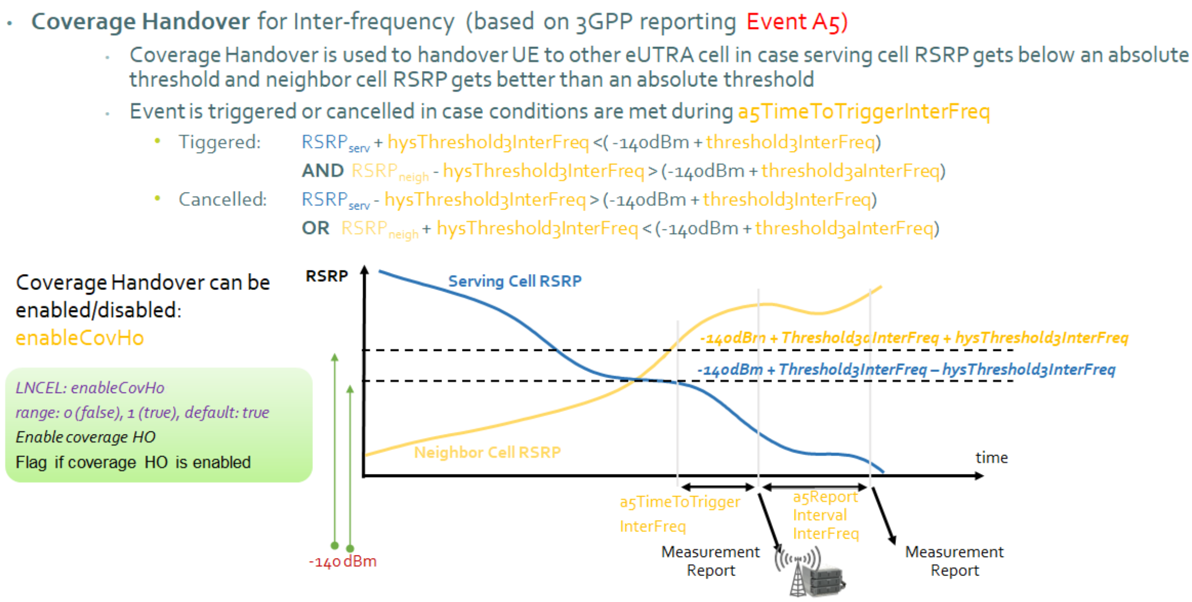


Figure 29: A5 event configuration

4.2. ES-PT Deployed Components

4.2.1. Overview of the deployed components

Table 27: ES-PT CBC Overview of Deployed Components

5G Networks											
	Operator & vendor	***NSA/SA***	**Num. gNBs**	**Freq. Bands**	**BW**	**TDD Frames**	**Network Sync**	**Backhaul**	**Core attributes**	**Core interconnect**	**Key HO / roaming param.**
Spain PLMN 1	Telefonica (Nokia ES)	NSA	4	First Phase: 4G: 800, 1800, 2100, 2600 MHz 5G: 3700 MHz	4G: 10-20 MHz 5G: 40 MHz		Time and phase	Fiber	CRAN vs DRAN, Fronthaul, etc.	Direct-fibre interconnection	Home-Routing, S10 based HO
Spain PLMN 1	Telefonica (Nokia ES)	NSA	4	Second Phase: 4G: 2600 MHz 5G: 3700 MHz	4G: 20 MHz 5G: 50 MHz		Time and phase	Fiber	CRAN vs DRAN, Fronthaul, etc.	Direct-fibre interconnection	Home-Routing, S10 based HO, LBO S10 based HO
Portugal PLMN 2	NOS (Nokia PT)	NSA	4	4G:, 2600 MHz 5G: 3700 MHz	4G: 20-20 MHz 5G: 100 MHz		Time and phase	Fiber	CRAN vs DRAN, Fronthaul, etc.	Direct-fibre interconnection	Home-Routing, S10 based HO
Portugal PLMN 2	NOS (Nokia PT)	NSA	4	4G: 2600 MHz 5G: 3700 MHz	4G: 20-20 MHz 5G: 100 MHz		Time and phase	Fiber	CRAN vs DRAN, Fronthaul, etc.	Direct-fibre interconnection	Home-Routing, S10 based HO, LBO S10 based HO
5G Features / Technologies / Configurations addressed											

(e.g., Home-Routing, Local Break-out, S1 base HO, S10 based HO, Direct line, SA slicing, Uu / PC5 communication, MEC/Edge based operation, Cloud based operation, multi-SIM, mmW etc.)

Vehicles & On-Board Units

Vehicles		Type	Make & model	SAE Level*	Vehicle Sensors	Vehicle capabilities / functions	OBUs		Developer / Vendor	Num. OBUs	Num. SIMs	OS	Sup. Mode	5G Chipset / Modem	OBU sensors
	Vehicle 1 / ES-PT_veh_03	Autonomous Car	Volkswagen Golf	3	Lidars, Cameras, Ultrasonic sensors, D-GPS	Autonomous driving (L3), lane merge, automated overtaking, sensors recording, internal map update, ITS communications		OBU 1	CTAG	5	1 SIM/ OBU	Linux	V2N	Quectel RM500Q-GL	GNSS
	Vehicle 2 / ES-PT_veh_01	Autonomous Car	Citroën C4 Picasso	3	Lidars, Cameras, Ultrasonic sensors, D-GPS	Autonomous driving (L3), lane merge, automated overtaking, sensors recording, internal map update, ITS communications		OBU 2	IT	1	1 SIM/ OBU	Linux	V2N	Quectel RM500Q-GL	GNSS
	Vehicle 3 / ES-PT_veh_02	Connected Car	Citroën C4 Picasso	1	Lidars, Cameras, Ultrasonic sensors, D-GPS	Manual driving, ITS communications		OBU 3	ISEL	4	3 SIM/ OBU	Linux	V2N	Thales Cinterion MV31-W Modem Card	GNSS
	Vehicle 4	Legacy Car	Citroën C4 Picasso	1	-	Manual driving									

	Vehicle 5	Connected Car	Citroën C4 Spacetourer	1	-	Manual driving, ITS communications									

***SAE Level used during trials**

Roadside & Other Infrastructure

MEC / Edge nodes	Num. Cloud instances	Num. RSUs	Num. ITS centers	Applications / User Stories	Message type	Supported interface	Supported protocols / APIs	Road side sensors	Supported mechanisms / Features
2	4	5	2	• Lane merge • Automated overtaking • VRU cooperation • HD maps • Remote Driving • 4K video surveillance • HD multimedia for passengers	CAMes, DENM, CPM, propietary messages	Uu	MQTT, SFTP, RTP, UDP, HTTP.	Pedestrian detectors, Traffic radars	Service discovery for MQTT brokers, Geoservers, Remote driving service, ITS communication, VRU detection, Vehicle detection
2 (ES&PT)	1 (for management)	NA	2 (ES&PT)	• Agnostic UC • Background Traffic • Network Stress	CAMes, DENM	Uu	MQTT, SFTP, RTP, TCP, UDP, HTTP.	NA	5G Network Performance Evaluation using Agnostic synthetic traffic Used also for network stressing using multiple OBU and 5G Modens

4.2.2. Measurement framework

The goal of 5G-MOBIX Project is to extract conclusions from the evaluation of the data gathered in the trials of each CBC/TS. Partners from the ES-PT consortium make use of a collection of tools, summarized in Table 28, with the aim of registering the behaviour of each variable.

In order to achieve reliable and comparable measurements, all the data registered must be synchronized. The lower part of this table summarizes the timing synchronization approaches applied to different entities.

Table 28: ES-PT CBC Measurement Tools

Measurement tools used in ES-PT CBC		
Tool Name	**Attributes**	**Details**
QLog	Description	Commercial tool (Qualcomm) to record data transmitted in the specific tests for Advanced Driving and Extended Sensors USs and also used in the agnostic test cases.
	PCO Level	Level 0
	PCOs used	OBUs and RSUs provided by CTAG
	Traffic injection	N/A
QMICLI	Description	Command line utility for the libqmi, a glib-based library for interacting with WWAN modems and devices, which support the Qualcomm MSM Interface (QMI) protocol.
	PCO Level	Level 0
	PCOs used	OBU and RSUs provided by IT and CTAG
	Traffic injection	N/A
G-NetTrack Pro	Description	Commercial tool used to monitor and log access layer values.
	PCO Level	Level 0
	PCOs used	5G enabled smartphones
	Traffic injection	N/A
TCPDump	Description	Open-source tool to capture data-network in the specific tests for Advanced Driving, Extended Sensors and Vehicle QoS Support USs.
	PCO Level	Level 1

	PCOs used	OBUs and RSUs provided by CTAG ES MEC ES and PT ITS Centers 5G enable smartphones
	Traffic injection	N/A
GoPCAP	Description	A simple wrapper around libpcap for Go language (https://github.com/akrennmair/gopcap). libcap is a portable C/C++ library for network traffic capture.
	PCO Level	Level 1
	PCOs used	OBU and RSUs provided by IT PT MEC
	Traffic injection	N/A
DEKRA Tool	Description	Commercial tool provided by project partner DEKRA to monitor network level communication between two (or more) devices.
	PCO Level	Level 1
	PCOs used	5G enable smartphones ES and PT MECs
	Traffic injection	N/A
Keysight Instrumented 5G SmartPhone	Description	Commercial tool from Keysight, using the Nemo Outdoor SW tool
	PCO Level	Level 0, 1 and 2
	PCOs used	5G intrumental Smartphone
	Traffic injection	iperf3 UDP and TCP Traffic loads.
IQ-NPE ISEL QoS – Network Performance Evaluation	Description	A multi PLMN and multi layer platform tool, specially developed for 5G CBC network QoS assessment.
	PCO Level	Level 0, 1 and 2
	PCO used	4 OBU with 5G modems each; 4 VM installed at MEC and ITS-Centre at ES and PT PLMN.
	Traffic injection	CAMes, DENM, SFTP, TCP, UDP, MQTT and HTTP
Proprietary Tools	Description	Tools designed ad-hoc by the ES-PT partners to collect application data in the specific tests for all the USs
	PCO Level	Level 2

	PCOs used	OBUs and RSUs ES and PT MECs ES and PT ITS Centers
	Traffic injection	N/A
Time Synchronization approaches used in ES-PT for different entities		
Synchronised entities	Applications running on Virtual Machines in the PT MEC are synchronized to a Stratum 3 NTP Server running on the MEC and redundantly synchronized to Stratum 2 NTP Servers from NOS in Lisbon and Porto ES MEC is directly synchronized via a dedicated fiber optics connection to a 5G RSU serving as time server, which is located in CTAG premises 5G OBUs and RSUs are synchronized via PTP with local time servers, which are synchronized through the Pulse Per Second signal from GNSS receivers NTP used for synchronization between VRU App and MEC.	
Measurements accuracy	<1ms in ideal conditions	
Measurements errors and correction techniques	Time synchronization accuracy is monitored in all network elements in order to examine the validity of the collected results	

Figure 30 illustrates the time synchronization architecture configured for ES-PT entities.

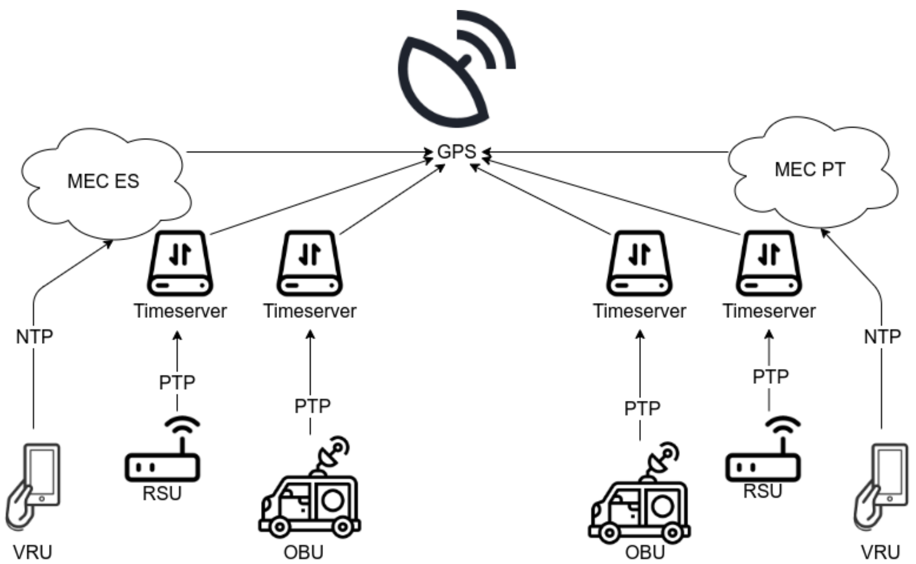


Figure 30: General view of time synchronization approach in ES-PT CBC

4.2.3. Difference to commercial networks / setups

The Telefonica Network is a separate PLMN dedicated to 5G-MOBIX devices, but radios used in the project are shared with commercial clients. The NOS network is a separate dedicated network.

4.3. TS Contributions to the CBC

Below is a brief summary of each of the contributions made by the STs to the ES-PT CBC. Each TS has travelled to the corridor to execute the planned contributions between September 2021 and April 2022, whereby they have found different states of maturity of the network deployment. These include Agnostic Tests and Specific Tests, as well as being planned for the different network configurations that were required in the ES-PT CBC, Home Routed and Local Breakout for the case of FI.

Table 29: Trial Site Contributions to ES-PT CBC

User Story	TS	CBC	Transferred Assets	Objective
Advanced Driving	FR	**ES-PT**	**5G Connected car** A 5G-connected vehicle will be transferred to test interoperability of a "foreign" car with ES-PT "local vehicles" and network. The transfer includes the 5G-OBU, a V2X protocol stack, KPI measurement tools and a QoS adaptive (predictive) module	• Testing of interoperability between FR vehicle and ES-PT 5G and digital infrastructure • Usage of multi-SIM solution during the use-case tests, in which FR TS vehicle connects with ES MEC and PT ME using multi-SIM in the overlapping coverage area.
	NL	**ES-PT**	**Standalone OBUs with 5G-Based MCS Application** The application supporting the Manoeuvre Coordination Service (MCS) [8] used in Cooperative Collision Avoidance (CoCA) user story will be transferred to the ES-PT corridor;	• Evaluate MCM/MCS communication framework and overtaking service with MCM at CBCs; • Testing the user story in border crossing situations.
Extended Sensors	DE	**ES-PT**	**MEC instances for EDM** MEC instances deployed in Telefonica's MEC and NOS MEC.	• Transfer and trial the complete DE user story "EDM-enabled extended sensors with surround view generation". • Testing the user-story under actual cross-border roaming conditions. • Comparing urban (Berlin) vs interurban (ES-PT CBC)
			MEC instances for video streaming WebRTC gateway MEC instances deployed in Telefonica's MEC and NOS MEC.	

				scenarios. Check influence of UE speed, UE density (commercial vs dedicated), cell subscription ping-pongs and shadowed areas. Testing the interoperability of RSU and ROI-based discovery service, Edge Dynamic Map (EDM) system with MEC Broker interconnection and video streaming based on WebRTC. • Comparing close MEC (ES-PT CBC) vs Far Edge (DE TS) performance.
			5G Multi-SIM OBU Solution – DE Transfer of two dual modem solutions, based on active-passive network bonding.	• Comparing DE's dual modem solution and ES-PT CBC's single-SIM roaming. • Testing UE compatibility (bands, drivers, firmware, etc).
			5G Connected and sensorised car VICOM's 5G-connected and sensorised vehicle was transferred/trialled in the CBC. The vehicle includes four calibrated cameras for surround view generation, DGPS, onboard computers, and 5G UEs with external antennas.	• Enabling trialling the end-to-end DE's Extended Sensors demo. • Testing interoperability with ES-PT CBC networks.
	FI	**ES-PT**	**Edge Discovery Service** Provides a DNS-like name resolution service to the MECs and the UE, allowing the vehicles to discover the IP of the MEC in each network domain;	• Assures application connectivity with ES and PT networks when passing from one country to the neighbouring • Enable uninterrupted HD video streaming (upload), for surveillance purposes.

Agnostic	FI	**ES-PT**	**5G Multi-SIM OBU Solution - FI** Transfer of Multi-SIM OBU with handover based on mobile IP tunnelling technology	• Benchmark handover latency parameters and service continuity against: • 5G NSA roaming with Single-SIM OBU implemented in ES-PT CBC; • Handover solution driven by a smart router provided by FR (see bellow);
	FR	**ES-PT**	**5G Multi-SIM OBU Solution – FR** Transfer of Multi-SIM OBU with handover based on smart router with link bonding capability.	• Benchmark handover latency parameters and service continuity against: • 5G NSA roaming with Single-SIM OBU implemented in ES-PT CBC; • Handover solution based on mobile IP tunnelling provided by FI (see above);

[1] 3GPP RP-193263 : Support for multi-SIM devices in Rel-17, 3GPP, 2020
[2] 3GPP SP-200091: Revised SID: Study on system enablers for multi-SIM devices, 2020
[3] https://www.gsma.com/esim/transforming-the-connected-car-market/
[4] https://www.ericsson.com/en/blog/2020/9/esim-driving-global-connectivity-in-the-automotive-industry

4.4. Updates During the Deployment Process

4.4.1. Radio Network Upgrades and Configurations

The radio nodes in the Spanish side were reconfigured several times during the project duration. The Telefonica network is in current commercial operation, so 4G and 5G nodes are used by real users. This implies that Telefonica is regularly upgrading the radio nodes firmware, and it is also deploying new radio features as they become available to support new 5G features and some radio optimizations.

In the first phase of the project, 4G anchoring for NSA configuration was deployed in all the 4G bands, providing more coverage to the project tests, but making it more difficult to test with the vehicles because it introduces a very high dependency on the 4G layer that is used by the vehicle to support the handover. When the vehicle is anchored in the lower bands, the network coverage reaches several kilometres away of the border of the two countries, so the handover is not executed in the specific road dedicated tests area. Then it was decided in a second phase to use only the 2600 MHz band for anchoring in Spain and in Portugal, what makes much more predictable and controllable where the handover takes place.

Figure 31 depicts the coverage of the radio cells of both Telefónica and NOS networks in the ES-PT CBC, with the indicative RSRP threshold levels to trigger the handover procedure. For instance, in the case of a vehicle leaving the area covered by NOS PCI #105 and entering Telefónica PCI #168, the handover will only be triggered when the RSRP value of NOS network signal in the 5G modem drops below –75 dBm and the one from Telefónica raises above 822 dBm.

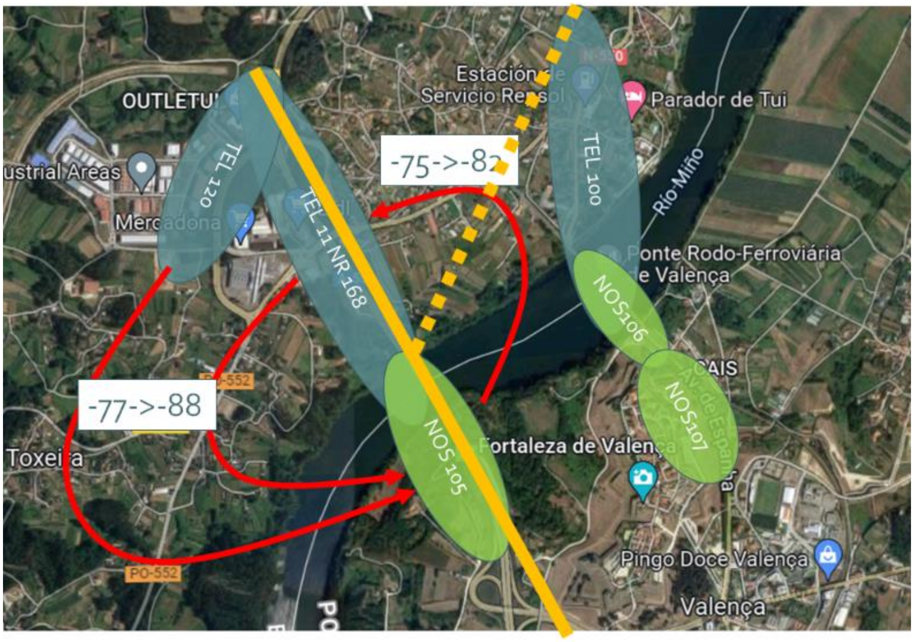


Figure 31: 5G network handover configurations in ES-PT CBC

Radio cells (A5, A1 and A2) parameters were configured in order to fix the area of handovers for the different use cases. Similar configurations were performed for the Portuguese network, however in this case there was more flexibility since the 5G radio network was only serving 5G-MOBIX project trials, not being shared with commercial users. In Table 30, one can see the parameters used to configure the handover mechanism with some example values for a specific trial run. These parameters are adjusted for each use story in order to obtain the handover event in the desired location for the target CAM manoeuvres. The configuration includes for instance the RSRP threshold values and the time to trigger the handover procedure.

Table 30: ES-PT CBC Radio Cell Parameters

		LNCEL		LNHOIF-16				
Cell	Band	Threshold2InterFreq	Threshold 2a	a3OffsetRsrpInterFreq	a3TimeToTriggerRsrpInterFreq	a5TimeToTriggerRsrpInterFreq	threshold3InterFreq	threshold3aInterFreq
TUI CENTRO 52	2600	-100	-98	3	160ms	128ms	-105	-90

		LNCEL		LNHOIF-16				
Cell	Band	Threshold2InterFreq	Threshold2a	a3OffsetRsrpInterFreq	a3TimeToTriggerRsrpInterFreq	a5TimeToTriggerRsrpInterFreq	threshold3InterFreq	threshold3aInterFreq
AS BORNETAS 54	2600	-114	-112	6	160ms	256ms	-92	-102

Location	Cell	PCI	Threshold2InterFreq	Threshold2A	threshold3InterFreq	threshold3aInterFreq
NEW_BRIDGE	31	104	-105	-102	-105	-90
NEW_BRIDGE	32	105	-105	-102	-105	-90
OLD_BRIDGE	33	106	-92	-90	-94	-100
OLD_BRIDGE	34	107	-92	-90	-94	-100

The cores are configured with home routed traffic to support a handover in the user plane without user plane interruption. This is only possible with home routed configuration, where vehicles' modems do not change the IP. The plan is to tests in the final phase of the project the local break out configuration.

Another important aspect related with the project deployment was the need to improve time synchronization for the applications running in the MEC nodes. For the Portuguese network from NOS, the architecture depicted in Figure 32 was employed. 5G-MOBIX Stratum 3 NTP servers are installed in bare metal on the 2 MEC physical servers, getting synchronization from Stratum 2 servers and delivering time sync to the applications running on the VMs. These Stratum 2 NTP servers from NOS infrastructure network are redundantly located in Lisbon and Porto, delivering time synchronization to the MEC virtualization environment.

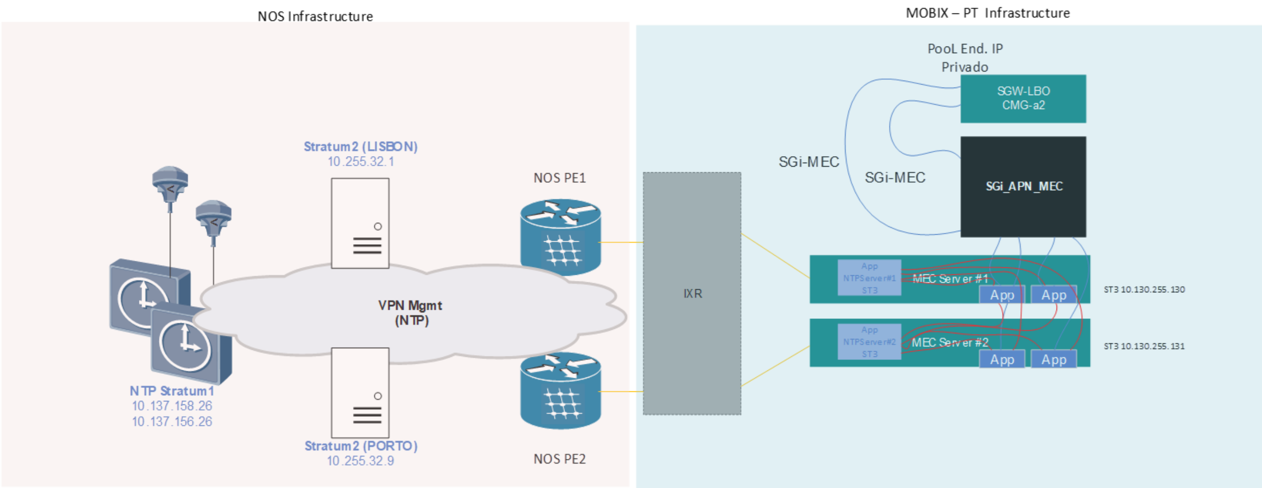


Figure 32: Time synchronization architecture for the PT MEC server applications

The synchronization accuracy tests were carried out with the Calnex Sentinel[5] equipment that allows error measurements to be obtained based on a GNSS reference, external source, or internal oscillator Rubidium (see Figure 33).

[5] https://www.calnexsol.com/en/product-detail/1033-sentinel

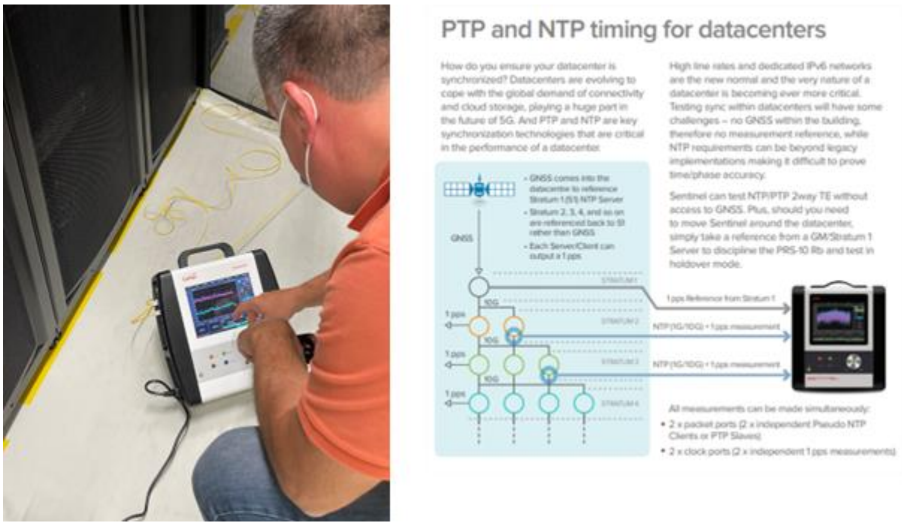


Figure 33: Calnex Sentinel equipment for time synchronization measurements

NOS carried out NTP time accuracy tests to evaluate time synchronization error and path delay at 8 sec sampling rate. Four different tests (as depicted in **Error! Reference source not found.**) were executed on t he Riba d' Ave data centre where MEC is installed:

- Test 1 – NTP reference on NOS IP/MPLS ERIP
- Test 2 – NTP on L2/L3 MOBIX Switching
- Test 3 – NTP on MOBIX MEC Servers
- Test 4 – NTP on MOBIX MEC vs NTP Reference

Tests 1, 2 and 3 were performed in order to evaluate the time synchronization accuracy that is possible to obtain through the existing NOS network in the PT MEC site. The obtained results showed that NOS NTP servers are very stable with a time error around 0,2 ms (worst case). On the other hand, Test 4 aimed to measure the synchronization accuracy at the NTP server (ST3) installed in the MEC node for the 5G-MOBIX project. The test was carried out using NOS NTP ST2 from Lisbon (10.255.43.1) as a reference for 5G-MOBIX NTP ST3. In this case, Calnex Sentinel was connected to 5G-MOBIX L2/L3 Switch Router to achieve L3 connectivity to NOS ST2 in Lisbon and 5G-MOBIX ST3 server#2 in Riba D'Ave (Figure 34).

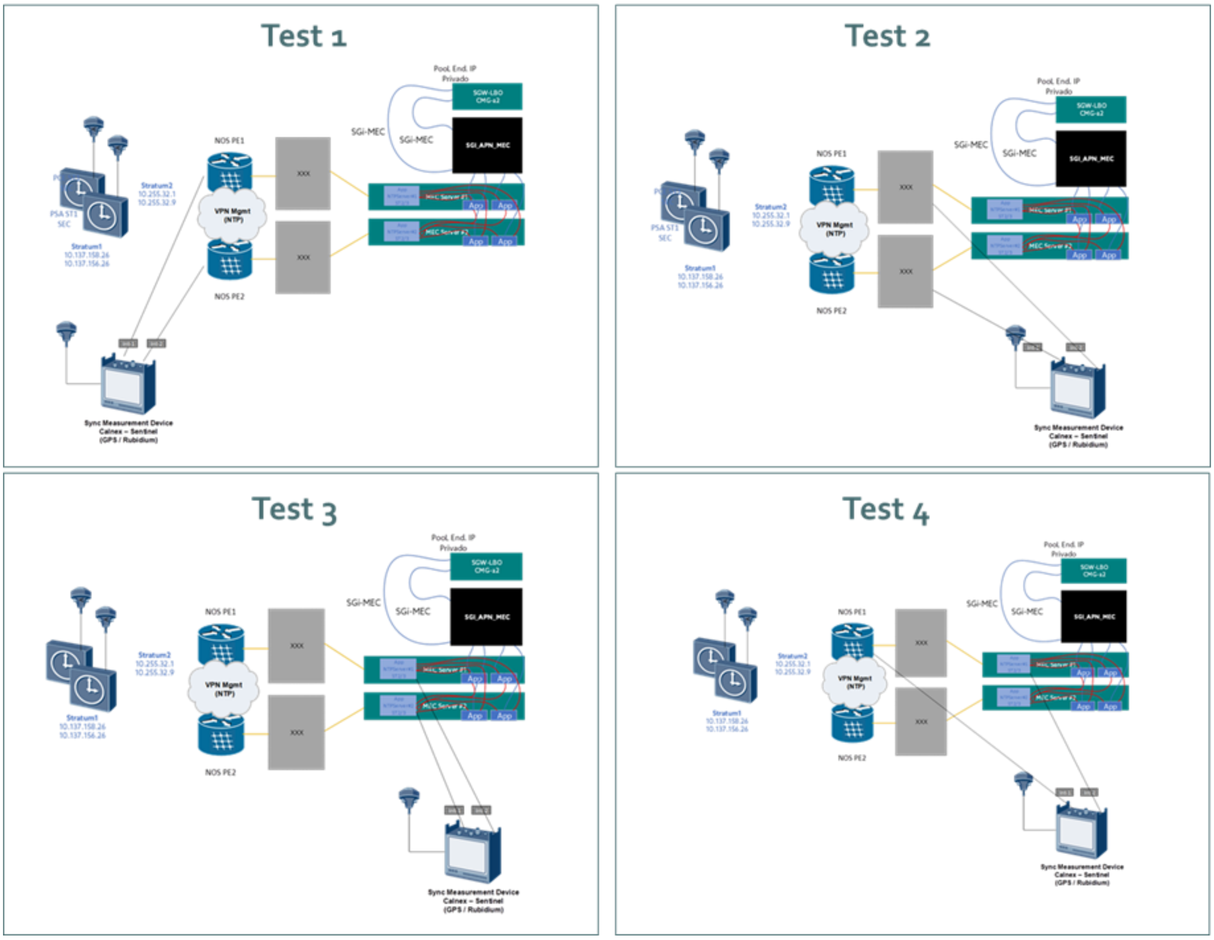


Figure 34: Time synchronization accuracy tests performed at the NOS network

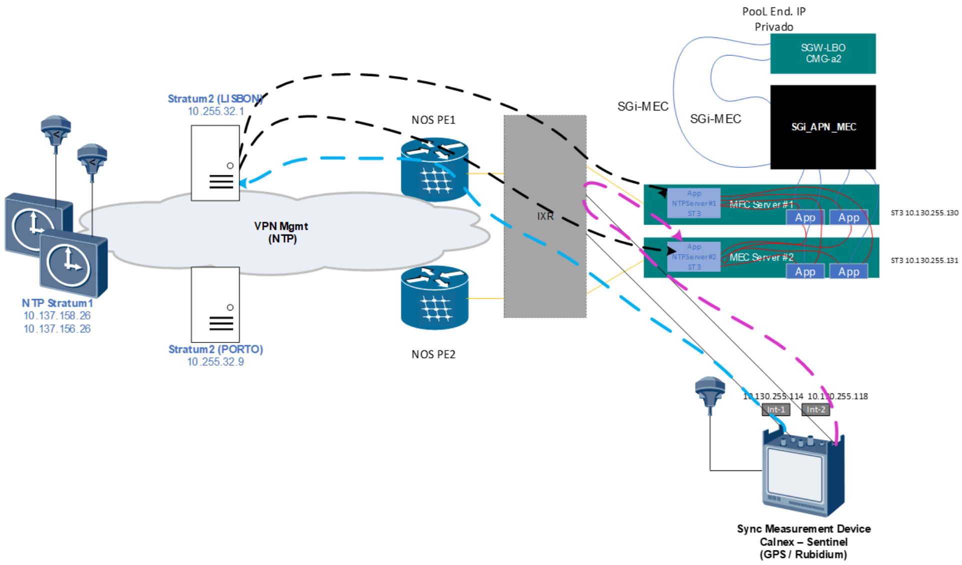


Figure 35: Time synchronization test (#4) performed at the PT MEC

Figure 36 shows the results obtained during the 18 hours that test 4 was running. In blue, one can observe that NOS NTP Stratum 2 is very stable with a time error around 0,2 ms. In pink, NTP Stratum 3 servers running on the MEC have a time synchronization error that ranges between 0,65 ms and -0,1 ms. The MEC sync error variation is likely due to the changing load on the servers where NTP servers are installed.

Figure 36: Time synchronization measurements obtained at the PT MEC

The obtained time synchronization results at the PT MEC were measured by comparing UTC reference achieved by Calnex Sentinel directly connected to a GNSS receiver and NTP analysis using NOS NTP servers versus 5G-MOBIX PT MEC NTP servers. These results show time synchronization compliance with the requirements from 5G-MOBIX user stories, which establish a synchronization error below 1 millisecond for the message timestamping at the application level.

4.4.2. MEC Geoserver Application

All CAM messages send by the different ITS stations, either 5G RSUs, OBUs or VRU App, are exchanged through the MEC MQTT brokers. There is a Geoserver application running on each MEC responsible for republishing the messages received in the inqueue topics to the outqueue and inter_mecs topics of the MQTT broker, as described in deliverable D3.4 [33]. During the design phase of the project, it was decided to also republish the incoming messages in all the adjacent tiles of the sending station. However, due to the heavy load that this task put on the MEC VMs during the deployment process, it was decided to modify the republishing strategy carried out by the Geoserver application, forwarding the inqueue messages solely to the outqueue topic with the same tile, leaving the task of subscribing to the adjacent tiles to the ITS stations.

4.5. ES-PT Verification Results

Delivarable D3.6 [34] shows that the verification process in the ES-PT CBC was almost complete at the time of the deliverable submission and only two out of the seven USs deployed in ES-PT, CoopAutom and MediaPublicTransport, have required additional actions after that. Table 31 shows the current status with the completion reaching 100% for all the USs. This chapter summarizes the effort carried out to complete these pending checks as well as some additional tests performed in the real scenario (the new bridge and the old bridge in the border between ES and PT), since the validation activities have been performed mostly in the CTAG's test tracks, without a completion of 100% validation on tracks, no use case goes out on the real road.

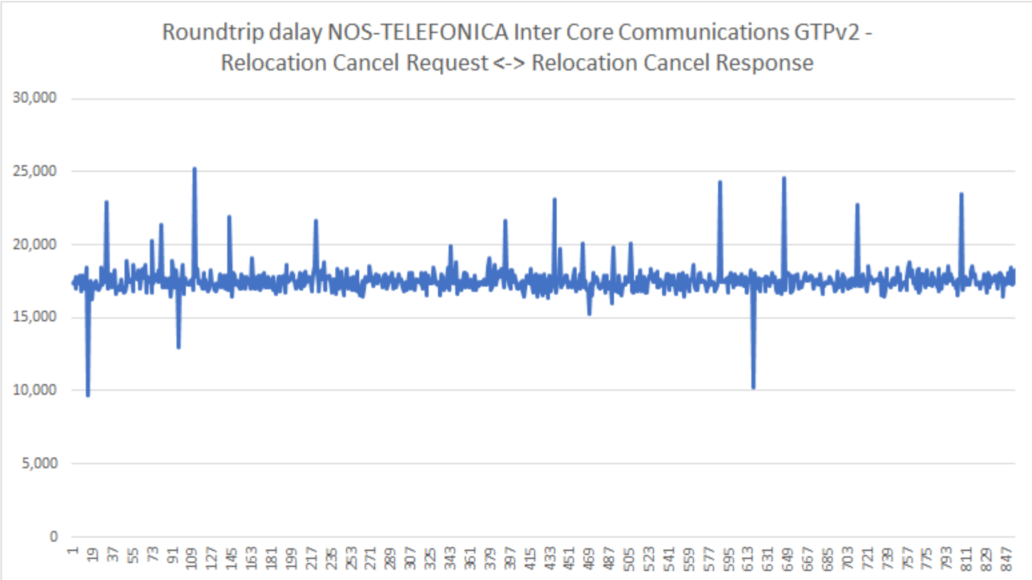
Table 31: Final verification results for the ES-PT CBC

User Story	Pass	Fail	Partly	Not tested	Completion %
LaneMerge	41	0	0	0	100
Overtaking	35	0	0	0	100
CoopAutom	47	0	0	0	100
HDMapsVehicle	40	0	0	0	100
HDMapsPublicTransport	40	0	0	0	100
RCCrossing	41	0	0	0	100
MediaPublicTransport	42	0	0	0	100

The activities during the last months in CoopAutom have been focused on the last developments of the app that is sending the CAM messages to the shuttle in order to warn about a pedestrian on the road. This app is already sending these messages being also synchronized, meaning that is ready to evaluate the UL dataflow between the smartphone and both the ES and PT MECs.

Regarding the MediaPublicTransport, some issues with the time synchronization of the devices due to a GPS antenna not working properly delayed the successful verification of the user story. After some tests and fixes, some new verification tests have been caried out to fine-tune the last adjustments, and to focus on the handover process which was successful from PT to ES using the Telefónica SIM. In addition, the processing tools have been evolved in order to check the synchronization and start working on the KPI calculation and the common data format.

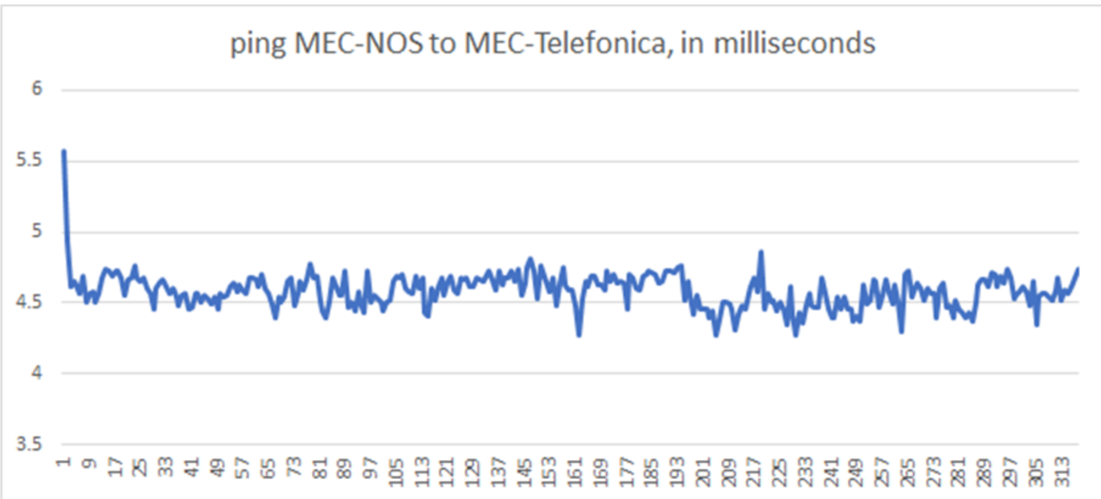
The tests focused on the characterization of the antennas, measuring throughput, latency and packet loss as more important KPIs. We have verified the transport link latencies between the central cores (MMEs), that is about 17 milliseconds as we can see in Figure 37.



End to end dalay
17,323
17,572
16,972
17,823
17,672
17,373
17,921
16,822
17,922
17,022
17,474
17,023
18,422
10,234

Figure 37: Roundtrip delay NOS-TELEFONICA Inter Core Communications

The dedicated fibre used for MEC and Distributed Cores interconnections has been verified, getting a result latency below 5 miliseconds, as depicted in Figure 38.



Pings ms
5.57
4.93
4.61
4.65
4.63
4.57
4.69
4.51
4.56
4.58
4.51
4.56
4.68
4.74
4.72
4.69
4.73
4.72

Figure 38: Ping MEC-NOS to MEC Telefonica

It has been verified with instrumental equipment and instrumental modems that handover parametrization is what was expected, as well as the user plane continuity during handovers with the configuration depicted in Figure 39.

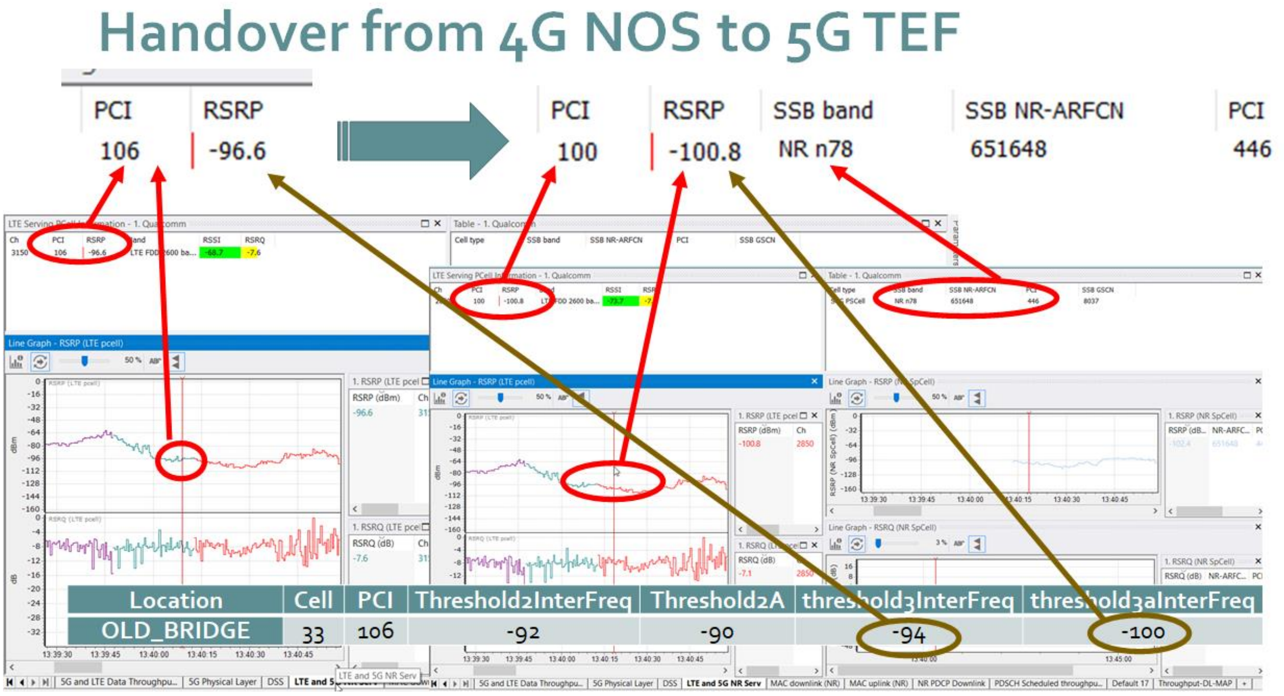


Figure 39: Handover from 4G NOS to 5G TEF

Finally, the network performance has been verified with CTAG vehicles equipped with Quectel modems taking traces in the gNodeB with millimetre details, but also in the vehicle. In Figure 40, a handover can be seen in the radio node events.

Handover from NOS 106 cell to TELEFONICA 100 cell
Traces from TELEFONICA 100 gNodeB

53	2/9/2022 17:05:10.750822	- Start trace -	
54	2/9/2022 17:05:10.750822		<--------------------- S1AP:HandoverRequest ---
55	2/9/2022 17:05:10.756464		--- S1AP:HandoverRequestAcknowledge ---------->
56	2/9/2022 17:05:10.886185		<------------------- S1AP:MMEStatusTransfer ---
57	2/9/2022 17:05:10.903679	--- eRRC:RrcConnectionReconfigurationComplete -->	
58	2/9/2022 17:05:10.904017		--- S1AP:HandoverNotify ---------------------->
59	2/9/2022 17:05:10.905656	<---------- eRRC:RrcConnectionReconfiguration ---	
60	2/9/2022 17:05:10.930693	--- eRRC:RrcConnectionReconfigurationComplete -->	
61	2/9/2022 17:05:10.932762	--- eRRC:MeasurementReport --------------------->	
62	2/9/2022 17:05:10.952708	--- eRRC:UlInformationTransfer ----------------->	
63	2/9/2022 17:05:10.952708	--- EMM:TRACKING AREA UPDATE REQUEST ---------->	
64	2/9/2022 17:05:10.952869		--- S1AP:UplinkNASTransport ------------------>
65	2/9/2022 17:05:10.952869		--- EMM:TRACKING AREA UPDATE REQUEST --------->
66	2/9/2022 17:05:11.051106		<---------------- S1AP:DownlinkNASTransport ---
67	2/9/2022 17:05:11.051106		<---------- EMM:TRACKING AREA UPDATE ACCEPT ---
68	2/9/2022 17:05:11.051496	<----------------- eRRC:DlInformationTransfer ---	
69	2/9/2022 17:05:11.051496	<------------ EMM:TRACKING AREA UPDATE ACCEPT ---	
70	2/9/2022 17:05:11.069634	--- eRRC:UlInformationTransfer ----------------->	
71	2/9/2022 17:05:11.069634	--- EMM:TRACKING AREA UPDATE COMPLETE --------->	
72	2/9/2022 17:05:11.069768		--- S1AP:UplinkNASTransport ------------------>
73	2/9/2022 17:05:11.069768		--- EMM:TRACKING AREA UPDATE COMPLETE -------->
74	2/9/2022 17:05:11.085857		<---------------- S1AP:DownlinkNASTransport ---
75	2/9/2022 17:05:11.085857		<--------------------- EMM:EMM INFORMATION ---
76	2/9/2022 17:05:11.085977	<----------------- eRRC:DlInformationTransfer ---	
77	2/9/2022 17:05:11.085977	<----------------------- EMM:EMM INFORMATION ---	

Figure 40: Handover from NOS 106 cell to TELEFONICA 100 cell

The same traces are registered in the CTAG vehicle while changing from one cell in NOS to the new cell in TELEFONICA, shown in Figure 41.

```
1644422710.851356629%%+QENG: "servingcell","NOCONN"
1644422710.865896962%%+QENG: "LTE","FDD",268,93,4D021,106,3150,7,5,5,1,-84,-8,-56,15,13,-100,-
1644422710.882379051%%+QENG: "NR5G-NSA",268,93,65535,-32768,-32768,-32768
1644422710.891460134%%
1644422710.900977903%%OK
1644422711.409184525%%at+qeng="servingcell"

1644422711.422590140%%+QENG: "servingcell","NOCONN","LTE","FDD",214,38,57ED616,100,2850,7,5,5,8EF9,-92,-8,-63,15,9,130,-
1644422711.431783561%%
1644422711.445607194%%OK
1644422711.891768973%%at+qeng="servingcell"

1644422711.901318744%%+QENG: "servingcell","NOCONN"
1644422711.909135436%%+QENG: "LTE","FDD",214,38,57ED616,100,2850,7,5,5,8EF9,-91,-9,-63,15,8,140,-
1644422711.920524624%%+QENG:"NR5G-NSA",214,38,65535,-32768,-32768,-32768,0,78,7,8
1644422711.928112305%%
1644422711.937139719%%OK
1644422712.608707494%%at+qeng="servingcell"
```

Figure 41: NOS 106 cell to TELEFONICA 100 cell traces from the vehicle

During the handover we have detected a maximum ping of 50 ms., in line with pings in the home network, as shown in Figure 42.

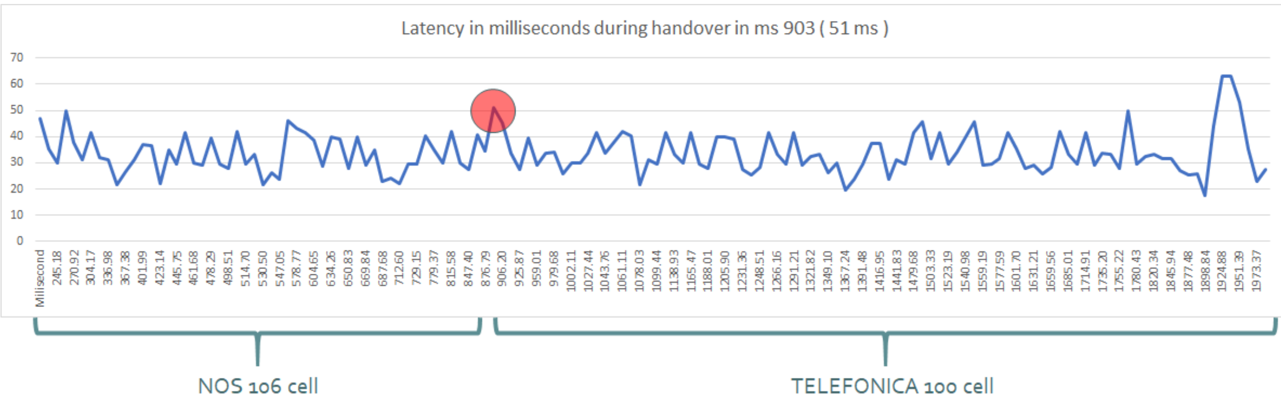


Figure 42: NOS 106 cell to TELEFONICA 100 cell handover latency

Figure 43 shows another handover obtained during the verification of the network performance where most relevant network parameters can be observed.

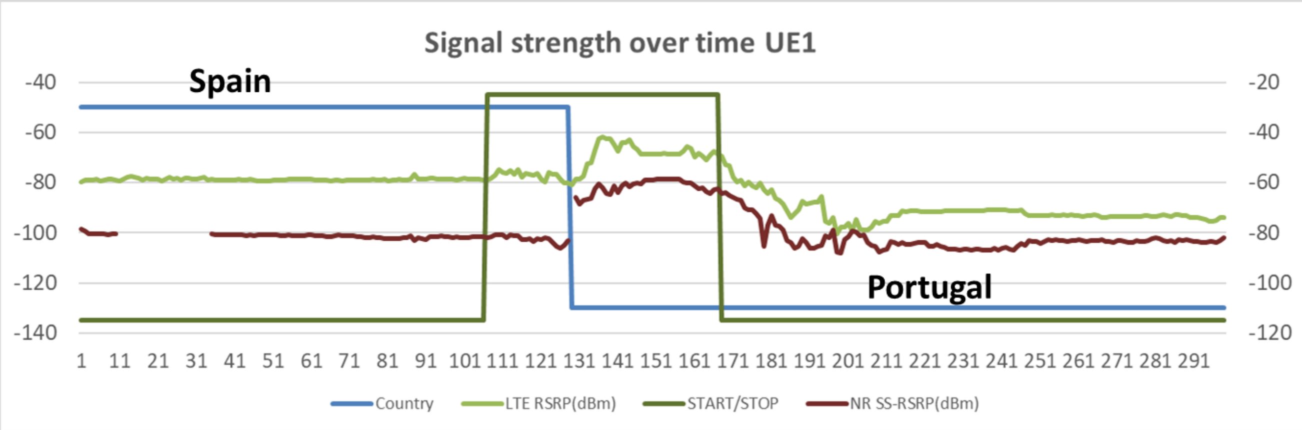


Figure 43: Handover signal strength during verification

The blue line shows the change of network operator from ES to PT while driving (handover), at the moment the RSRP threshold condition is fulfilled. After the handover, the 5G signal strength, becomes stronger. The RSRP scales for LTE (left) and NR (right) are shifted, so the graphic becomes clearer. The START/STOP line shows the period where the manoeuvre is performed, with the handover during the overtaking action.

The map in Figure 44 shows the trajectory followed by the car and the exact location where the handover is produced (yellow mark).

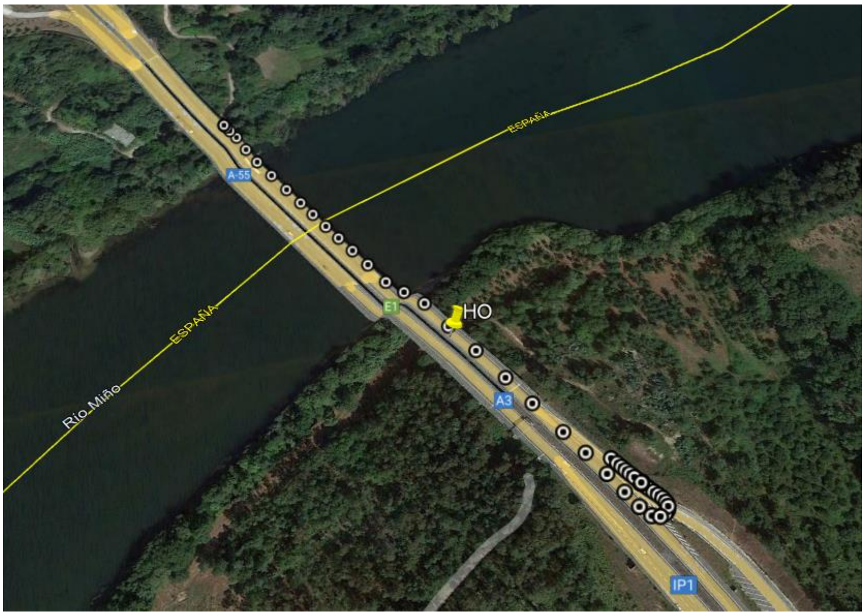


Figure 44: Trajectory for handover signal strength during verification

Finally, Table 32 shows the most relevant handover procedures performed at the vehicle side.

Table 32: Handover procedures performed

Time	Duration (s)	RAT	Layer	Protocol Procedure	System Procedure	Result	Extra Info	RAT	ARFCN
02:58:37	0.09	LTE	EMM	Service Request		OK	{}	LTE	2850
02:58:37	0.09	LTE	RRC	Connection Establishment		OK	{"Establishment Cause": "mo-Data", "TMSI": "0xc0200641"}	LTE	2850
02:58:37	0.01	LTE	RRC	Connection Reconfiguration	Radio Bearer Configuration	OK	{"Measurement ID": [1, 2, 4, 7, 14, 17], "EARFCN": 2850, "PDCP Config": true, "NR Radio Bearer Config": true}	LTE	2850
02:58:38	0.01	LTE	RRC	Connection Reconfiguration	NR RRC Reconfiguration. Radio Bearer Configuration	OK	{"Measurement ID": [1, 2], "PDCP Config": true, "NR Config": "setup", "EN-DC ReleaseAndAdd": false, "NR Secondary Cell Group Config": true, "NR Radio Bearer Config": true}	NR	2850
02:58:38	0.01	NR	RRC	Connection Reconfiguration	Radio Bearer Configuration. RLC Bearer Addition. SpCell Configuration	OK	{"Cell Group ID": 1, "Logical Channel Identity": 4, "SpCell Index": 8, "NR PCI": 168, "NR ARFCN": 651648}	NR	2850
02:58:38	0.02	NR	MAC	Random Access		OK	{"SSB ID": 0, "CSI RS ID": 0, "Content Type": "CONT_UL_GRANT"}	NR	2850
02:58:38	0	LTE	RRC	Connection Reconfiguration	NR RRC Reconfiguration	OK	{"NR Config": "setup", "EN-DC ReleaseAndAdd": false, "NR Secondary Cell Group Config": true}	NR	2850
02:58:38	0	NR	RRC	Connection Reconfiguration		OK	{"Cell Group ID": 1}	NR	2850
02:58:41	0	LTE	RRC	Connection Reconfiguration		OK	{"Measurement ID": [5, 6, 14, 15]}	NR	2850
03:00:12	0.04	LTE	RRC	Connection Reconfiguration	EN-DC Release. Radio Bearer Configuration. Intra-System Handover	OK	{"EARFCN": 3150, "PCI": 105, "DRB Identity": 4, "PDCP Config": true, "NR Config": "release", "NR Radio Bearer Config": true}	LTE	3150
03:00:12	0	LTE	RRC	Connection Reconfiguration		OK	{"Measurement ID": [1, 2, 4, 7, 17]}	LTE	3150
03:00:12	0.15	LTE	EMM	Tracking Area Update		OK	{"Request Active APN": [5]}	LTE	3150
03:00:13	0	LTE	RRC	Connection Reconfiguration		OK	{"Measurement ID": [5, 6, 14, 15], "EARFCN": 2850}	NR	2850
03:00:13	0.02	LTE	RRC	Connection Reconfiguration	NR RRC Reconfiguration. Radio Bearer Configuration	OK	{"Measurement ID": [1, 2], "PDCP Config": true, "NR Config": "setup", "EN-DC ReleaseAndAdd": false, "NR Secondary Cell Group Config": true, "NR Radio Bearer Config": true}	NR	3150
03:00:13	0.02	NR	RRC	Connection Reconfiguration	Radio Bearer Configuration. RLC Bearer Addition. SpCell Configuration	OK	{"Cell Group ID": 1, "Logical Channel Identity": 4, "SpCell Index": 8, "NR PCI": 105, "NR ARFCN": 641376}	NR	3150
03:00:13	0.06	NR	MAC	Random Access		OK	{"SSB ID": 2, "CSI RS ID": 0, "Content Type": "CONT_UL_GRANT"}	NR	3150
03:00:14	0	NR	RRC	Connection Reconfiguration		OK	{"Cell Group ID": 1}	NR	3150
03:00:14	0	LTE	RRC	Connection Reconfiguration	NR RRC Reconfiguration	OK	{"NR Config": "setup", "EN-DC ReleaseAndAdd": false, "NR Secondary Cell Group Config": true}	NR	3150

We have also verified from the Core Networks the number of handover, attempts and successes, as depicted in Figure 45.

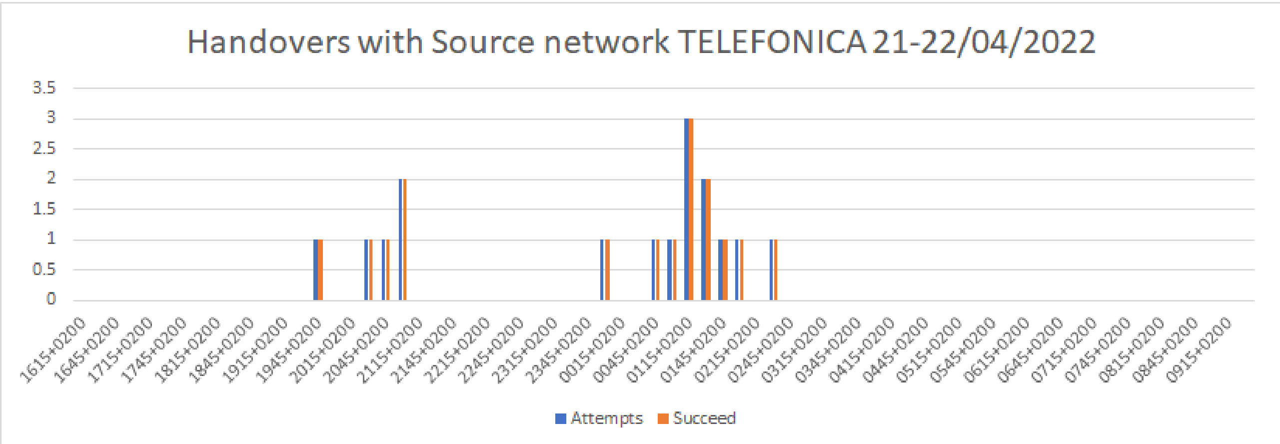


Figure 45: Handovers with Source Network TELEFONICA

4.6. ES-PT Deployment Challenges & Lessons Learned

The IPX/GRX providers allow Mobile Network Operators (MNOs) and other service providers to efficiently connect their IP based networks to achieve roaming and inter-working between them. However, in the current architecture, the IPX/GRX networks increase latency because the exchange hubs are not geographically distributed in a logic of delivering services at the operators' edge. Direct interconnection between MNOs is a solution to reduce latency but it is not scalable because it will require the one-to-many IP connections across multiple cross-border edges. This problem will be as greater as the length of the borders and the number of operators involved. The IPX standard will have to evolve to be able to meet the requirements of critical low latency services.

RAN deployment requires a collaboration between both sides of the border. Typically, transmission power and coverage are configured to avoid interferences on the frontier, causing some coverage area gaps. In this context, it was important to ensure an optimized coverage area on the frontier to obtain an overlapping between the national network and the target network in the frontier. This is something that was achieved in ES-PT CBC through the deployment of new sites or reorienting the existing ones to optimize the coverage at the border areas, considering the foreign network in the optimization process. RAN parameters thresholds are configured to avoid undesirable transfers and ping-pong on the nearby towns but ensuring at the same time smooth handovers with the foreign network through the overlapping of coverage areas. Required a jointly fine tuning on the RAN parameters.

The deployment using commercial network from Telefonica was selected since the start of the project, so the deployment was focused in 5G NSA network deployment. The main purpose of the consortium was to provide the most efficient handover coverage in the corridor between Spain and Portugal, so it was decided to deploy a distributed core in NOS in Portugal and interconnect both using a dedicated line instead of Internet access between countries (using Internet peering access between both operators). We decided to interconnect the cores through the S10 interface to optimize the handover transference between the networks. The following main challenges drive our main decisions:

4.6.1. Band for anchoring the 5G

It is needed to provide maximum performance in terms of bandwidth and latency to vehicles, so initially it was decided to support the 5G anchoring in all the 4G bands in the border of Spain and Portugal, but when the first field tests were conducted it was discovered that coverages were very extensive, but the following challenges were encountered:

1. Test results rely on the 4G band where the vehicle was initially anchored when the test started. If vehicle was connected to lower bands, bandwidth tend to be lower, latency grater, and it cannot be guaranteed the required network performance to some use cases and vehicles

2. It was observed that depending on the 4G band layer the handover procedure starts in very distant points, but in some cases even several kilometers away from the border of the two counties coverage from the home PLMN was still present and there was no handover

3. Performance relies on the commercial network concurrency, so at peak hours test results were affected significantly by the network

In order to palliate these challenges, it was restricted the V2X 5G-MOBIX anchoring band to 2600 MHz because this band is not very used in the border area in the two roads, there is more bandwidth for the use cases when needed and it is possible to keep a better and predictable control of the handover location to tests with real autonomous vehicles. The following lessons were learnt:

1. Coverage in radio could not be as relevant for some use cases as performance, so lower coverage using higher bands will be more suitable in many deployments

2. Multiple Bands coverage is not always a good solution when some critical KPIs must be guaranteed, mainly in case that the radio bands provide different performance

3. Dedicated bandwidth is always the best method to guarantee a given performance to a limited number of users

4.6.2. Commercial Network coexistence

Telefonica Mobile Network in Spain is a mobile network with many different mobiles technologies, many bands, and many subscribers. Then there are some critical challenges that are relevant for the V2X deployments:

1. Firmware updates in the radio nodes when needed at national level. The radio nodes evolve as new optimizations or fixes are available, these updates use to be deployed in massive deployments updates in thousands of nodes in a few days. These updates sometimes require reparameterization of radio nodes that are not compatible with V2X customizations.

2. New features activation as needed by the introduction of new features is ongoing. New radio features activation at national level to support for instance new Carrier Aggregations, implies change in the radio nodes that mandatory need specific reparameterization after the changes.

3. Coexistence with real user traffic in the radio nodes implies performance constraints.

4. Security and robustness must be guaranteed in order to not affect the Commercial clients. This implies additional tests to the new parametrization of the antennas and specific permissions and validation from operational Telefonica experts to guarantee no impact on service.

It is expected in future real deployments of V2X services these similar challenges will be detected, so some lessons that have been learnt in the project are:

1. Automatic regression tests will become more critical as new V2X services will become available, mainly because the potential impact on some CAM uses cases maybe higher.

2. It is needed to separate in radio, transport and cloud slices the resources allocated to CAM services and to the rest of the clients.

3. Deployment time for new V2X services may take more time than previous commercial services already deployed in telco mobile networks, as security and robustness may take more time.

4.6.3. Deployment of V2X in networks with several Public Land Mobile Networks

The decision to support the deployment of a dedicated PLMN identifier and network in the Telefonica Mobile Network as a new virtual mobile operator, has several challenges that had to be managed:

1. Radio nodes and radio layers can be parametrized at different levels, some of these parameters are defined at radio node, at radio layer, or applied only to specific PLMNs. Then it is possible to change only some parametrization of the radio nodes without affecting to the rest of the users supported in other PLMNs not related to CAM V2X.

2. The radio nodes are configured to have one main PLMN identifier, and then several additional PLMNs can be added.

Some limitations and problems have been found for the optimal configuration of the radio nodes without affecting other users, so we have the following lessons learnt:

1. The Multiple Bands radio could have some implications when some of the bands are configured with multiple PLMNs, as a reconfiguration on one PLMN may affect other PLMNs as a side-effect.

2. Nodes configured with several PLMNs may need specific configuration in some bands that must be independent on the configuration on other bands.

4.6.4. Handover Events A1, A2 and A5 constraints

Radio levels for launching the Handover procedures when changing from one operator to a different operator may be configured using 3GPP standardized events, using Events A1, A2 and A5 Events. These are the selected events to implement radio handover:

- Event A1: Serving becomes better than threshold, deactivation of measurements
- Event A2: Serving becomes worse than threshold, activation of measurements
- Event A5: SpCell becomes worse than threshold1 and neighbor becomes better than threshold2

The configuration of the parametrization of these events implies the following challenges:

1. The activation and deactivation of the Measurement Reports (events A1 and A2), these are the messages the UE sends to the gNB with the connected radio levels and the neighbors measured radio levels, is controlled by the configuration of the minimum RSRP level in the connected radio layer to start these radio measurements, and the minimum RSRP level in the connected radio layers to stop these radio measurements. These levels depend on the modem device and modem antenna.
2. The activation of the Handover procedure in the gNB (event A5) is configured with minimum RSRP level in the connected radio network and minimum level in the neighbor radio network. These RSRP levels depend on the modem device and modem antenna.
3. In order to cause the Handover procedure in a known area of the road, these levels must be configured carefully to execute some CAM use cases inside a known road area.
4. We have not configured A3 event that launch the Handover procedure using only RSRP gap between connected radio network and neighbor radio network, but we do not want to launch the Handover with low radio levels that cannot guarantee the minimum KPI requirements, so we discarded using A3 event.

Some of the lessons learnt from the radio levels configuration are the following:

1. The optimal configuration for a modem, antenna and vehicle may be very different to other combination of these components.
2. Ideally for most of the use cases, the Handover preferred location is well known in advance, what may change from one vehicle to another are the RSRP values in this position
3. All connected vehicles have GPS so using A1, A2 and A5 plus some GPS handover authorized location (geofencing) would be ideal to support controlled handovers in very well-known locations.

4. Activation of Measurement Reports may impact on the performance of some vehicles modem.

5. Activation of Measurement Reports in a massive deployment may impact some old models of gNBs that may receive many Measurement Reports per second.

4.6.5. Dedicated fibre line to improve V2X handover performance

The use of a connected fiber line between operators improves drastically the latency of the messages between the two MECs and the messages between the two distributed cores when messages are interchanged in the border of the two networks.

The following challenges have been identified:

1. Connecting operators in two different countries may be implemented using peering in the higher aggregation routers of each operator, which requires the packets to run on many kilometers of fibre and cross many interconnection routers.

2. Connecting operators in two different countries may be implemented also by dedicated fiber lines connected to access networks in the same operator.

The lessons learnt with this particular deployment are:

1. For efficient V2X message interchanges in border countries there should be dedicated lines connecting both networks. These lines currently do not exist between operators for V2X services.

5. GR-TR CBC DEVELOPMENT, INTEGRATION & ROLL-OUT

5.1. Site Overview

The Greece-Turkey (GR-TR) CBC is one of the two cross-border corridors in 5G MOBIX project. It is located at the Kipoi-Ipsala border region between two countries. 5G Non-Stand Alone (NSA) 3GPP Rel. 15 [35] networks have been deployed on each side of the border covering a total of 9.9 kms of Highway with 4 gNBs. Within this corridor four 5G enabled CAM user stories have been implemented and trialled in cross-border conditions namely, **i)** 5G enabled truck platooning, **ii)** Platooning with "see what I see" functionality, **iii)** Extended sensors for assisted border crossing and **iv)** Autonomous truck routing in customs area. Turkcell, Cosmote and Ericsson (GR and TR) are providing the 5G networks, Ford Otosan is providing the autonomous trucks, WINGS ICT Solutions, ICCS, IMEC and Tubitak are providing the On-Board Units (OBUs) and CAM applications. Figure 46 depicts the GR-TR CBC location and layout and a high-level overview of two use cases.

Figure 46: The GR-TR CBC location & layout

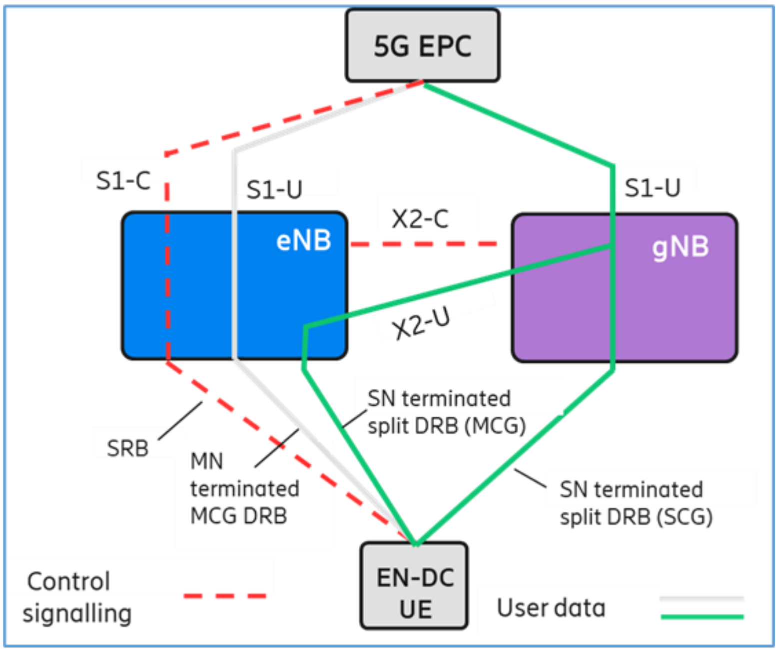


Figure 47: NR NSA Option 3x Architecture

New overlay compact 5G networks (NSA 3.x option) have been deployed by both operators Cosmote and Turkcell, connected to dedicated RAN infrastructure deployed for the purpose of the 5G-MOBIX trial. Specifically, a new RAN overlay network has been deployed to minimize impact on the commercial RAN services as well as provide the freedom for frequent SW release upgrades of the network domains. The deployed RAN architecture is compliant to 3GPP R15 NSA [35] Op.3x architecture, in which the eNB acts as the Master Node (MN) and the gNB as the Secondary Node (SN), as depicted in Figure 47. In fact, the LTE layer, which is used as an anchor layer to the NR carrier, is deployed at 2.6GHz with a carrier bandwidth of 20MHz, while the gNBs are deployed at 3.5 GHz with a carrier bandwidth of 100 MHz using an AAS (Advanced Antenna System), a solution that iprovides cell shaping and Massive MIMO. Specifically, the radio access network defines 1-sector coverage using the following RAN network components:

- Radio Units (passive and active):
    - Passive remote radio unit with SU-MIMO 2x2 capability for enabling LTE technology with an instantaneous bandwidth (IBW) carrier of 20 MHz in band B7 (2620-2690) MHz.
    - Active Antenna System (AAS) massive MIMO 64T64R capable transceiver unit. The AAS is used to operate an NR carrier of 100 MHz IBW operating in B42F (3420-3600) MHz band.
- RAN Compute eNB & gNB units controlling the radio connection with the connected vehicles as well providing Radio Resource Management (RRM) including connection mobility control.
    - 2 Separate RAN compute baseband units are used for RAN LTE and NR applications. The first baseband will act as radio access processing platform for the LTE SW providing anchor layer for the control plane according to NSA option 3x implementation. The interface towards the distributed radio unit will be based on CPRI transport protocol.

- The second baseband will act as radio access processing platform for the 5G NR protocol providing OBU connectivity to the 5G vEPC via 5G NR user plane.
- Ericsson Network Management System for fault, configuration and performance management.

Apart from the dedicated RAN infrastructure deployed for the purpose of the 5G-MOBIX trial, the functionalities of Evolved Packet Core (EPC) and User Data Consolidation (UDC) have been deployed. In addition, the supporting OSS (Operations Support System), which is a software component that enables a service provider to monitor, control, analyse, and manage the services on its network, has been deployed. The overlay core networks serve only 5G-MOBIX users since no other type of users are allowed to connect to the network.

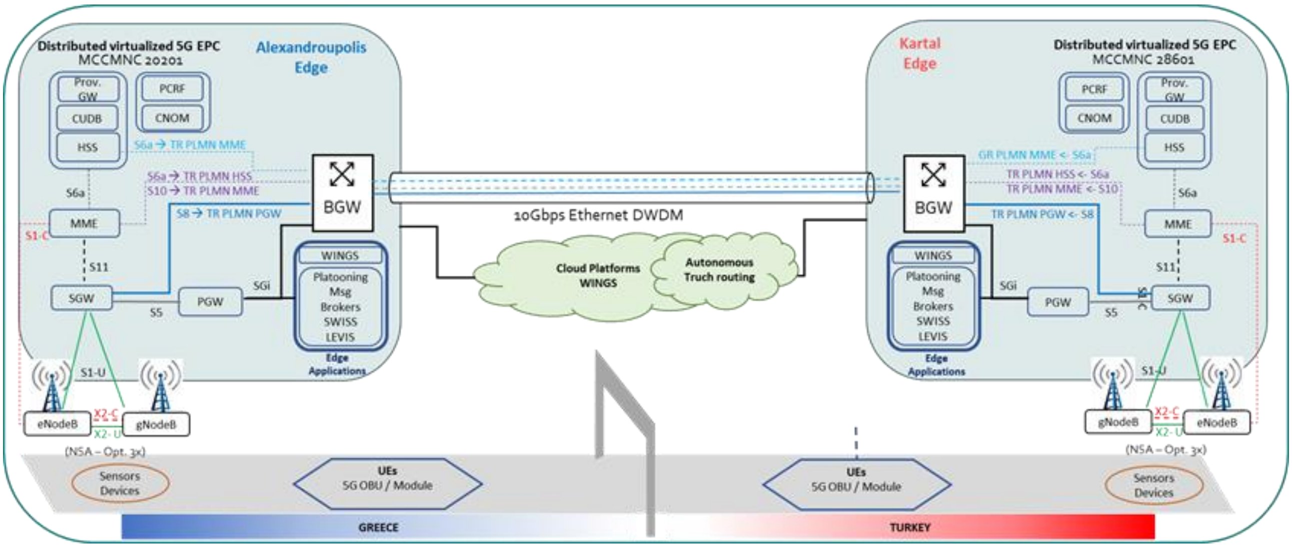


Figure 48: Overall Architecture

The 5G Core Elements and the edge application servers reside at the same edge DC. MEC servers' connectivity with the 5G Core Elements is realized via PGW Sgi interface within the DC. Sgi interface is extended to the external private clouds to connect to Applications hosted in the private clouds (e.g., Platooning) as well as to allow remote management activities.

Inter operator connectivity is ensured by one of the two 3GPP roaming standards called as Home Routed (HR) and Local Break Out (LBO). For both HR and LBO scenarios, the interconnection of MNOs can be established through GRX/IPX networks or direct connection. In order to fulfil the strict latency requirements imposed by the 5G-Mobix use cases, an overlay direct interconnection between the two MNOs has been implemented. Specifically, a 1Gbps Ethernet unprotected DWDM circuit was leased by OTEGLOBE and used for the direct interconnection of both MNOs.

For the purpose of Home Routed Roaming following interfaces are integrated:

- S6a: It enables transfer of subscription and authentication data for authenticating/authorizing user access to the evolved system (AAA interface) between MME and HSS.
- S8: Inter-PLMN reference point providing user and control plane between the Serving GW in the VPLMN and the PDN GW in the HPLMN. S8 is the inter PLMN variant of S5.
- S10: Reference point between MMEs for MME relocation and MME to MME information transfer. This reference point can be used intra-PLMN or inter-PLMN (e.g., in the case of Inter-PLMN HO).

Neighbouring PLMNs are configured as Equivalent PLMNs (ePLMN – list of allowed PLMNs) in the MME which is transferred to the eNB (relayed over S10 by the T-MMEs) in the Handover Restriction List in the Initial Context Setup Request, in the Handover Request and the Tracking Area Procedures. Static MME and PGW selection (IMSI based) is configured by both networks. IMSI a unique number that is assigned to each SIM card, to identify users in the network.

For the purpose of LBO, in order for the visited MME to select the visited PGW, the Static Gateway Selection mechanism is used. The association between the APN and the serving PGW will hint to local PGW rather than to the remote PGW for the visited MME. The APN control mechanism is based on dedicated APN using the "APN Local Breakout Control" function in the MME.

5.2. GR-TR Deployed Components

5.2.1. Overview of the deployed components

Table 33: GR-TR CBC Overview of deployed components

5G Networks											
	Operator & vendor	***NSA/ SA***	**Num. gNBs**	**Freq. Bands**	**BW**	**TDD Frames**	**Network Sync**	**Back haul**	**Core attributes**	**Core interconnect**	**Key HO / roaming param.**
Greece PLMN 1	COSMOTE	NSA op.3x	1	B7 :3050 N78 : 636666	LTE 20Mhz NR 100Mhz	TDD 383 (SCS:11:3:0)	GPS	2 Gbps (MW+ Fiber)	Virtualized Packet Core,	1 Gbps direct	EN-DC mobility SgNB addition LTE HO
Turkey PLMN 2	TURKCELL	NSA op.3x	3 In border 1 In Eskisehir	B7: 2850 N78: 646666	LTE 20Mhz NR 100Mhz	TDD 383 (SCS:11:3:0)	GPS	1Gbps (MW + Fiber)	DRAN, Virtualized Packet Core, Fronthaul (eCPRI	1 Gbps direct	EN-DC mobility SgNB addition LTE HO

5G Features / Technologies / Configurations addressed
(e.g., Home-Routing, Local Break-out, S1 base HO, S10 based HO, Direct line, SA slicing, Uu / PC5 communication, MEC/Edge based operation, Cloud based operation, multi-SIM, mmW etc.)
COSMOTE: 5G NSA, based on virtualized EPC Architecture. Dedicated Network (Core & RAN) for the V2X applications, implemented at the EDGE site. Node deployed: HSS, CUDB, MME, SGW, PGW, CNOM*, ENM*, EDA*). 3GPP Interfaces Deployed: S1-MME, S1-C, S1-U, S5/S8, S10, S11, S6a, S6d, Sgi COSMOTE's underlying NTP (Stratum -1) infrastructure is re-used to synchronize 5G-EPC/RAN for date and time synchronization **TURKCELL:**

5G NSA, based on virtualized EPC Architecture (CUPS Architecture).
Dedicated Network (Core & RAN) for the V2X applications.
Node deployed: MME/SGW-C/SGW-U/PGW-C/PGW-U/ CNOM*
Turkcell's underlying NTP (Stratum -1) infrastructure is re-used to synchronize 5G-EPC/RAN for date and time synchronization.

* Ericsson provisioning and operational supporting functions for the 5G NSA nodes

ROAMING:

- **HR Roaming with Session Continuity:**
    - S1 Handover Configuration and Neighboring PLMN(s) definition in RAN. Neighboring Cells for each frequency.
    - S8 and S10 Interfaces. EPLMN and Neighboring PLMN(s) definition in MME/eNBs.
    - Configuration of UE and APN restrictions in MMEs.
    - Static IMSI based PGW selection configuration. IMSI based GW selection in TR network for inbound roamers from GR, will point to GR PGW. Similarly, IMSI based GW selection in GR network for inbound roamers from TR, will point to TR PGW
    - Options for interconnection: 1) via direct line 2) IPX.

- **LBO without session continuity:**
    - S1 Handover Configuration and Neighboring PLMN(s) definition in RAN. Neighboring Cells for each frequency.
    - EPLMN and Neighboring PLMN(s) definition in MME/eNBs.
    - Configuration of UE and APN restrictions in MMEs.
    - Static IMSI based PGW selection configuration. Static IMSI based PGW selection configuration. IMSI based GW selection in TR network for inbound roamers from GR, will point to TR PGW. Similarly, IMSI based GW selection in GR network for inbound roamers from TR, will point to GR PGW
    - Options for interconnection: 1) via direct line 2) IPX.

RAN features:

- Control Channel Beamforming
    - Proprietary implementation of common channel cell shaping provides additional coverage gain vs. industry common implementation
- Ericsson Uplink Booster
    - High performing Physical Uplink Shared Channel (PUSCH) receiver for NR improving uplink coverage and superior interference suppression in all types of radio environments
- Massive MIMO Mid-band
    - single-user MIMO (SU-MIMO) is supported in downlink with up to four layers, and in uplink with one layer

- LTE-NR Downlink Aggregation
  - The LTE-NR Downlink Aggregation feature enables increased user peak bit rates by simultaneously transmitting downlink data on the LTE and the NR carriers of the EN-DC split bearer
- LTE-NR Uplink Aggregation
  - TE-NR Uplink Aggregation can improve uplink user throughput
- Physical Layer Mid-Band
  - The deployment of NR in mid-band allows to access 3.5GHz spectrum offering low latency services and higher data rates. DDDSUUDDDD (4 downlink + 2 uplink + 4 downlink) – the equivalent of LTR TDD UL/D configuration 2 is used with 6:4:4 SSF. Transform Precoding Disabled (CP-OFDM) is supported both in downlink and in uplink. Modulation schemes are supported up to 256 QAM in downlink and up to 64 QAM in uplink. 30 kHz subcarrier spacing is supported on mid-band.
- Intelligent Connectivity
  - EN-DC allows the early introduction of 5G in a Non-Standalone deployment.

Vehicles & On-Board Units

		Type	Make & model	SAE Level	Vehicle Sensors	Vehicle capabilities / functions			Developer / Vendor	Num OBUs	NumSIMs	OS	Sup. Mode	5G Chipset / Modem	V2V module	OBU sensors
Vehicles	**Vehicle 1**	N3, Truck	Ford, F-MAX	L4	Camera, Radar, RTK-GNSS	Precise Positioning, Autonomous Maneuvers, V2X Communication, Emergency Stop, Path Following, Platooning Maneuvers, Video Sharing	OBUs	**IMEC OBU**	IMEC	2	2	Linux	V2N, V2V	Quectel RM500Q	Cohda MK6c (PC5)	GNSS
	Vehicle 2	N3, Truck	Ford, F-MAX	L4	Camera, Radar, RTK-	Precise Positioning, Autonomous		**WINGS OBU**	WINGS	1	1	Linux	V2N	Quectel RM500Q		GNSS, proximity, CO2,

					GNSS, Lidar, CO_2 sensor, NFC sensor	Maneuvers, V2X Communication, Emergency Stop, Path Following, Platooning Maneuvers, Video Sharing										acceleration, NFC
	Vehicle 3	-	-	-	-	-		**WINGS OBU**		1	1					

Roadside & Other Infrastructure

MEC / Edge nodes	Num. Cloud instances	Num. RSUs	Num. ITS centers	Applications / User Stories	Message type	Supported interface	Supported 146ulfil 146l / APIs	Road side sensors
2	1x WINGS cloud 1x Tubitak Cloud	3	0	1. 5G Platooning 2. See What I See 3.Assisted Border Crossing 4 Autonomous truck routing	CAMes, DENM, proprietary	Uu, PC5	MQTT, HTTP, LiDAR	UHD camera, x-ray machine

5.2.2. Measurement framework

Table 34: GR-TR CBC Measurement Tools

Measurement tools used in GR-TR CBC		
Tool Name	**Attributes**	**Details**
DEKRA Performance Tool	DEKRA has a testing solution to cover the needs of vendors, application developers and telecom operators for the performance and the relevant KPIs measurement. It is composed of a Controller and as many Agents as needed for the measurements.	This is a commercial tool used in the specific testing for the Platooning "See-What-I-See" US (See-What-I-See).
	PCO Level	Level 2
	PCOs used	The application server and the application client devices
	Traffic injection	Not applicable in the use case of the See-What-I-See US
NEMO Outdoor	Nemo Outdoor is a laptop-based drive test tool for 4G, and 5G NR mobile network testing which supports commercial devices and scanning receivers, from various vendors, all the latest network technologies, and latest smartphones. Nemo Outdoor offers a full drive test solution for wireless network testing / mobile network testing, troubleshooting, and optimization.	This is a commercial tool used in the agnostic tests.
	PCO Level	Level 0
	PCOs used	PCOs: eNB/gNB used by the tool in the agonistic tests conducted in the CBC.
	Traffic injection	IPERF2 will use for synthetic traffic injection.
TEMS Investigation	TEMS Investigation, network testing solution, allows to test every new function and feature in the mobile networks. This allows to better understand Customer Experience and to verify, optimize and troubleshoot to mobile network. It allows for testing all wireless technologies like GSM/GPRS/EDGE, WCDMA/HSPA/HSPA+, CDMA2000 1x/EV-DO, WiMAX, LTE and 5G.	This is a commercial tool used in the agnostic tests.
	PCO Level	Level 0

	PCOs used	PCOs: eNB/gNB used by the tool in the agonistic tests conducted in the CBC.
	Traffic injection	IPERF2 will use for synthetic traffic injection.
Probe & Assistant	The Probe is an air interface test software, which is used to collect the test data of the air interface of the GSM/GPRS/EDGE, WCDMA/HSPA/HSPA+, CDMA2000 1x/EV-DO, WiMAX, LTE and 5G network. Through the Probe, the network performance can be evaluated, the network optimization can be guided, and the fault can be rectified. The collected test data of the air interface on the radio network can be saved as the test log file. This facilitates the data analysis after the log file is imported to other post-processing software (such as GENEX Assistant) or the later data replaying.	This is a commercial tool used in the agnostic tests.
	PCO Level	Level 0
	PCOs used	PCOs: eNB/gNB used by the tool in the agonistic tests conducted in the CBC.
	Traffic injection	IPERF2 will use for synthetic traffic injection.

Time Synchronization approaches used in <CBS/TS> for different entities							
Synchronised entities	COTS Smartphone	IMEC OBU	Wings OBU	IMEC RSU	Edge	Cloud	…
Method/Approach	For Agnostic tests: Commercial smart phones used. There is no time synchronisation required with other NW nodes. (Appliable for NEMO and TEMS)	NTP service running on the OBU. Time synch is based on USB GNSS device using PPS signal		NTP service running on the RSU. Time synch is based on USB/Serial GNSS device using PPS signal			
Measurement's accuracy		1 ms		1 ms			
Measurements errors and correction techniques		At OS level, NTP service will use the PPS signal to achieve accurate time synch		At OS level, NTP service will use the PPS signal to achieve accurate time synch			

5.2.3. Difference to commercial networks / setups

In terms of 5G-MOBIX project, both Cosmote and Turkcell networks have deployed overlay dedicated networks, apart from transport infrastructure, while they both made use of their commercially known PLMN-IDs.

In terms of cross-network interconnection, Turkcell and Cosmote commercial networks are currently connected through GRX network so that subscribers of both MNOs can obtain services from the visited network and related traffic traverses through GRX networks while roaming. Specifically, both MNOs support in their commercial networks Home Routed (HR) roaming scenario and their networks are interconnected through the interfaces S6a and S8.

In terms of 5G-MOBIX project, the overlay networks of Cosmote and Turkcell are interconnected via a dedicated leased line, required to fulfil the strict latency requirements imposed by the 5G CAM applications. Both Home Routed (HR) and Local Break Out (LBO) scenarios are supported. Specifically, in terms of HR roaming scenario, apart from S6a and S8 interfaces, the interface of S10 was also activated aiming to ensure service continuity while crossing the borders. Figure 49 depicts the interconnection of necessary network functions deployed in Turkcell and Cosmote networks in order to realize home routed roaming scenario. The interfaces that both networks of MNOs are connected through are as following:

- S6a is used for interconnecting the MME of the V-PLMN with the HSS located in the H-PLMN
- S8 is used for signalling and data transfer between the SGW/PGW entities.
- S10 is introduced as an additional roaming interface in order to exchange context information between two MMEs and ensure service continuity while crossing the border.

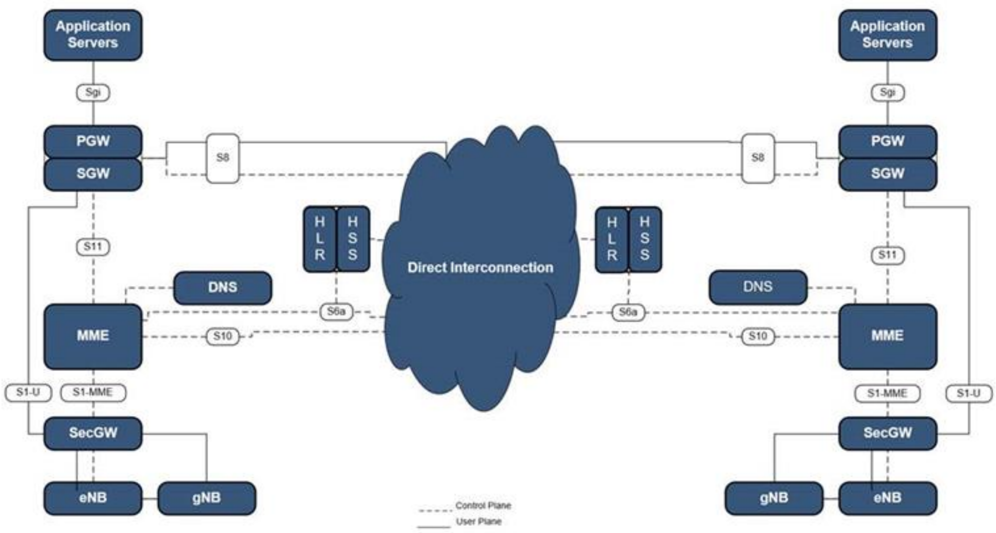


Figure 49: Overall Architecture Interconnection between Turkcell and Cosmote

Both Cosmote and Turkcell PLMNs are defined as Equivalent PLMNs (e.g. EPLName = TR, MCC=286,MNC = 1) within the defined Geographical Areas for the IMSIs used in the trial. Due to the fact the commercial network PLMN IDs are used in the trial for the overlay networks, MOBIX UEs were attempting to attach to Turkcell's or Cosmote's commercial networks. After rejected from the network, the UEs were not attempting attach to Mobix. In order to avoid this, restriction applied to all trial IMSIs to Turkcell's and Cosmote's commercial networks to avoid attach requests.

In terms of LBO roaming scenario, which is also supported by the interconnected MNOs, the APN control mechanism is based on dedicated APN using the "APN Local Breakout Control" function in the MME. Specifically, APN Local Breakout Control for roaming subscribers is configured by using following setup:

1. Enabling required "apn_local_breakout_control" in MME.
2. Set the LocalBreakoutMode parameter to restricted if only some of APNs specified by VPLMN-address-allowed in the subscription data are allowed for local breakout.
3. Specify the APNs allowed and associate the local breakout profiles with an IMSI number series.
4. The APN definitions is also required in the EPG node to allow the UE for PDN creation.

Finally, it should be noted that system and sites redundancy, and enterprise services such as DNS and Diameter Edge/Routing Agent (DEA/DRA) that are part of the commercial deployments and not in 5G-MOBIX due to its overlay nature, will need to be included upon the CBC actual commercial launch. It should be stressed that especially edge site redundancy becomes important for the application architecture as, apart from the network services, the applications located at the edge need to instantly fail over to another instance.

5.3. TS Contributions to the CBC

In the following table, the other 5G-MOBIX TSs contributions to the GR-TR CBC are described. In the case of GR-TR CBC only the FI TS contributed with the provision, instalment, tests and further supervision of LEVIS binaries.

Table 35: Trial Site Contributions to GR-TR CBC

User Story	TS	Contribution to CBC
Vehicle Platooning with "See-What-I-See" functionality	FI	**LEVIS Video Streaming** LEVIS video streaming application developed at FI trial site. LEVIS video streaming application in FI TS carried out within the remote driving user story context in a 5G multi-PLMN environment. Its binaries referring to both LEVIS application server and the corresponding client devices were remotely installed to the respective GR-TR equipment. Prior to the installation, modifications were made for the successful use of LEVIS in platooning user story in GR-TR CBC, as high-resolution video streaming is going to be shared between vehicles in a

		platoon to enhance safety and driving experience. Part of trials in the CBC, involved testing of continuity of this critical video stream under different roaming mechanisms (HRO and LBO) between the 5G NSA networks on either side of the GR-TR CBC.

5.4. Updates During the Deployment Process

This section presents new developments that were not foreseen in the initial design and implementation phase. These primarily refer to constraints of the deployment area and early trial findings and are reported specifically per site.

5.4.1 Physical optimization activities

For end users to benefit effectively from the established network, it must be properly optimized. During the deployment period, the following studies were carried out on the sites in Greece and Turkey. The main purpose of these studies is to improve network performance.

5.4.1.1 GR Site

In order to prevent the installed Cosmote antenna from overshooting to the Turkish side, a RET (remote electrical tilt) equipment was installed to reduce the service area. In this way, the Cosmote antenna was prevented from serving undesirable areas (Tuned cell 3420_KIPI).

Commercial LTE site is used for NR anchoring (Cosmote Site ID 3120 KIPIX). Commercial LTE antenna was used, with existing azimuth 155°, and existing mechanical tilt -3°(uptilt). This antenna combined with the specific mechanical tilt has a propagation of 20km (KPI below is from the codirectional commercial cell in 1800MHz).

In order to mitigate any overshooting, electrical tilt of 8° was applied in the LTE Mobix Cell. For the NR cell, dedicated Active Antenna was used with azimuth 145°. Mechanical tilt was finally set to 3° (down tilt) and digital tilt to 4° in order to achieve optimum coverage of the bridge and the surrounding area (from the Greek customs to the Turkish customs). Cosmote antenna direction is shown in the Figure 50 below. Additionally serving area statistic is shown in the Figure 51.

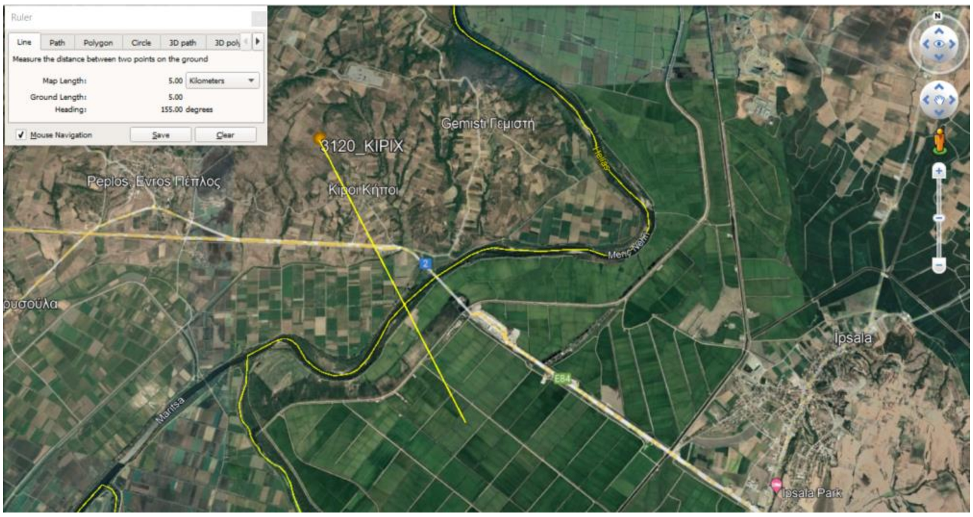


Figure 50: Cosmote antenna direction

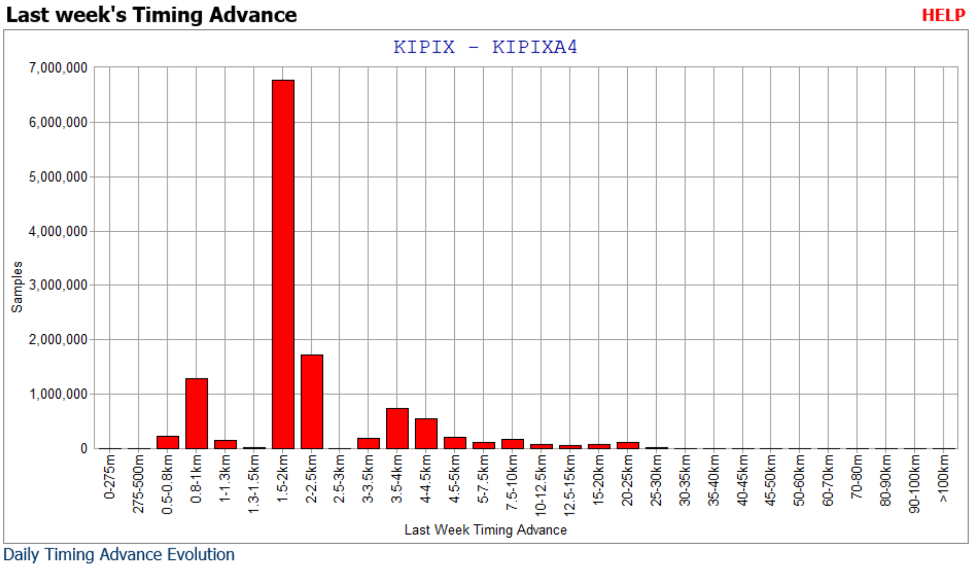


Figure 51: Serving area statistics of the Cosmote cell

5.4.1.2 TR side

Before starting the parametric optimization studies, it was checked whether the NW operating with default parameters gives the expected performance. In the following section, the problems encountered, and the applied solutions are explained.

In the project legacy LTE NW is used for NR anchoring. Access NWs are designed for commercial users. Some of the antenna directions are not focused on the 5G-MOBIX test route and these are overshooting un-wanted locations. Besides, LTE and NR coverages are not overlapping. To overcome this problem some physical activities have been carried out.

- One of Turkcell's LTE antenna has been disconnected from the commercial network antenna and a separate LTE antenna was added. Antenna direction has changed 300° to 240° to focus on wanted service area. Signals from this sector were previously overshooting the GR customs zone. (Tuned cell IPSLA2, see Figure 52).

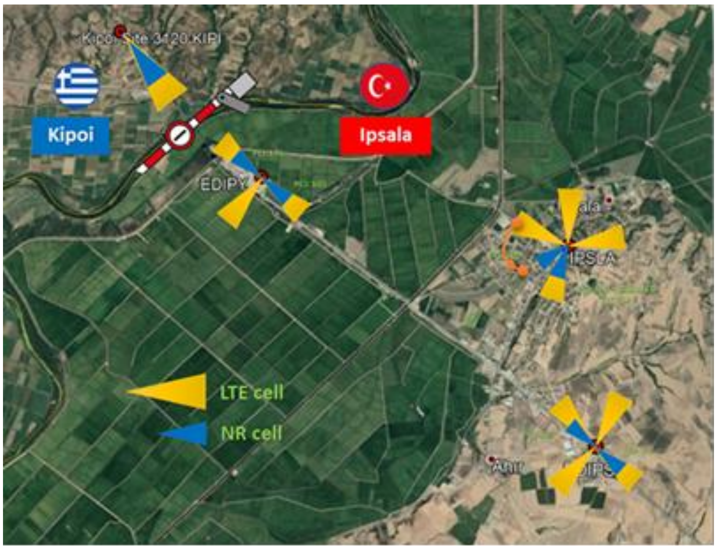


Figure 52: GR-TR CBC Overview of deployed components

- During the field controls, it was observed that the UL throughput values were not sufficient for the Turkcell Network. Below, Figure 53 is illustrating Serving cell PCI and Uplink throughput performance during mobility test.

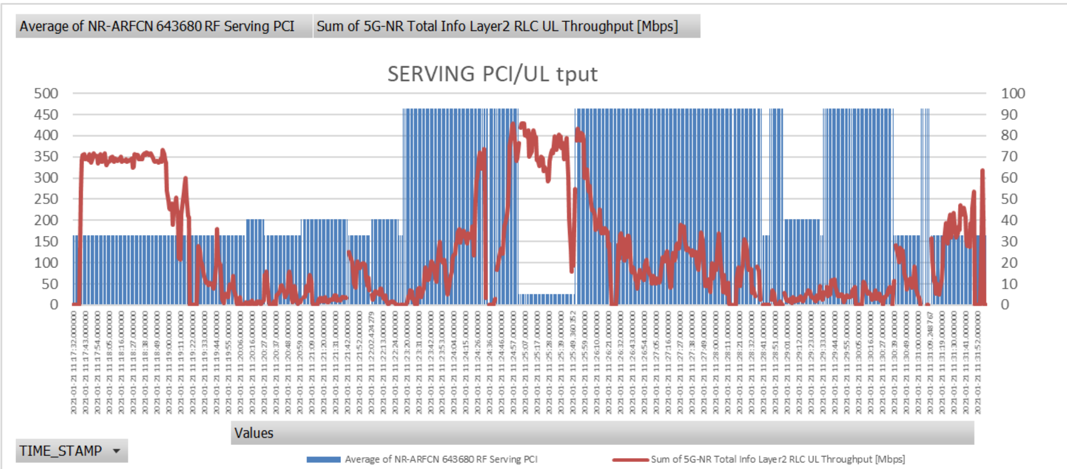


Figure 53: Serving cell and Uplink throughput performance before tuning

To solve the problem,

- The used LTE bandwidth from 5Mhz was increased to 20Mhz by utilizing the benefit of NSA Option3x.
- Electrical Tilt optimization for the LTE and NR antennas.

- Performed parametric optimization activities which are explained in Parameter optimization section.

The Figure 54 shows the UL throughput performance achieved after the changes.

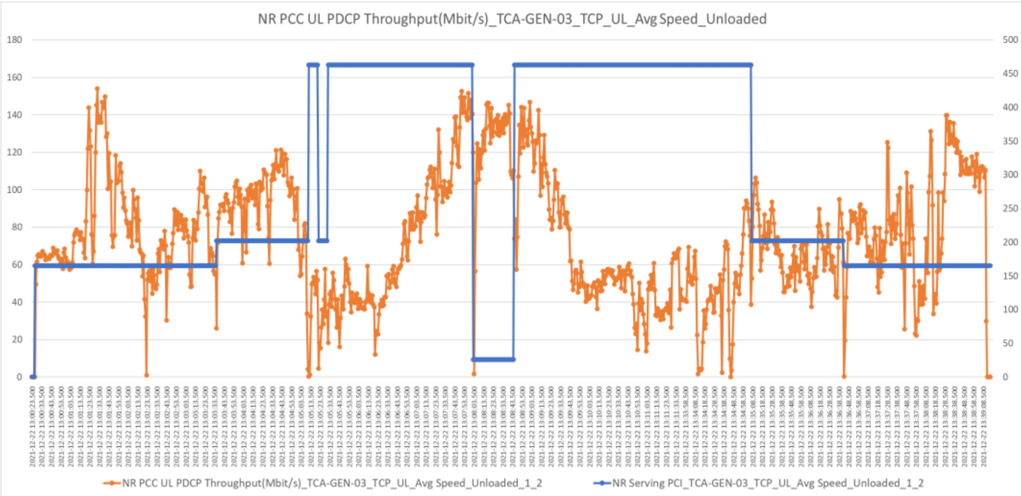


Figure 54: Serving cell and Uplink throughput performance after tuning

5.4.2 Parameter optimization

After solving the physical implementation problems, various parameter optimizations were made to maximize the NW performance. Below detailed information about the studies carried out is provided.

- Activating LTE – NR Uplink and Downlink carrier aggregation.
- endcMeasTime: This parameter used for search time period to adding suitable NR leg into the SCG. It is possible that the Secondary Node Addition procedure is not successful when the period set for the endcMeasTime attribute expires. Setting that parameter to -1 allow UE continues NR frequency search for ENDC setup. Below Figure 55 is illustrating how UE Measurement Control parameter mechanism works.

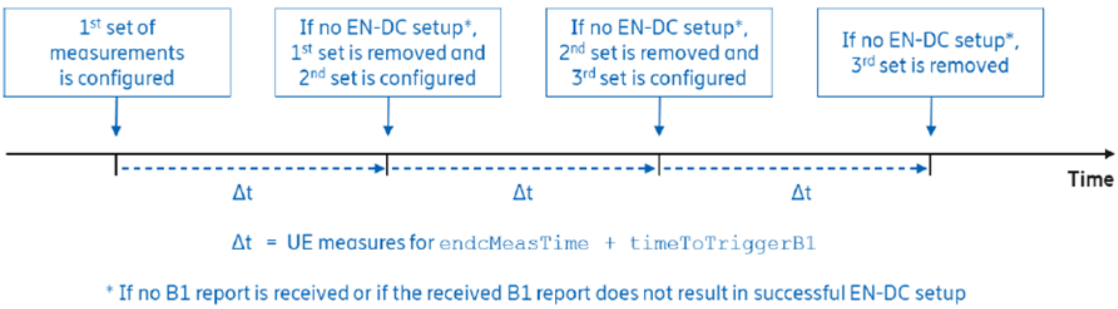


Figure 55: UE Measurement Control

The Figure 56 below shows the default and set values of the endcMeasTime parameter in Turkcell-Cosmote NW.

Parameter	Default	Range	Unit	Setting for Turkcell	Setting for Cosmote
endcMeasTime	2000	-1, 40 to 120000	msec	-1	-1

Figure 56: endcMeasTime parameter default and set values

Since Turkcell and Cosmote use different frequency bands in the project, they need to perform Inter-Frequency HO when moving between the two networks. For this purpose, optimization of Event A5 parameters was made at GR-TR border crossings. If these parameters are not set correctly, it will not be possible for users to perform HO at the desired location.

A1a2SearchThreshold, a5Threshold1Rsrp and a5Threshold2Rsrp are used primarily for coverage triggered inter-frequency handover. The mechanism is working as described below; specifically, when the UE enters the search zone using a1a2SearchThreshold, serving cell becomes worse than a5Threshold1Rsrp+Hyst and neighbor cell becomes better that a5Threshold2Rsrp+Hyst after Time to Trigger period, IFHO trigger.

The Figure 57, below shows how the mechanism of the EventA5 parameters works. By tuning these thresholds, it can be controlled under which conditions and where handover approximately occurs. In order to use these parameters effectively, Mobility Control at Poor Coverage (MCPC) feature has been activated. (Feature details explained below)

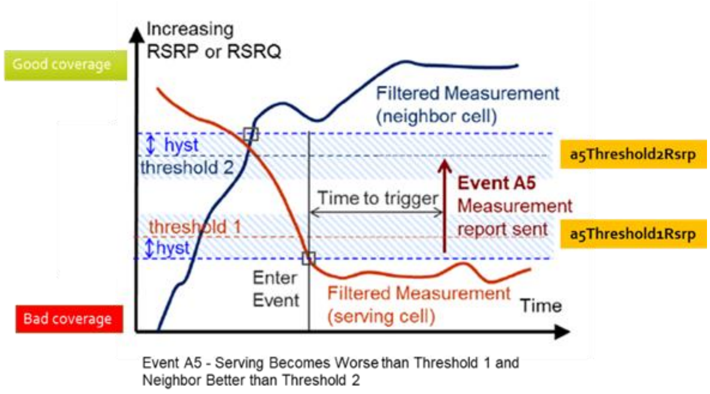


Figure 57: Event A5 parameters working mechanism

The Figure 58 below shows the default and set values of the EventA5 parameter in Turkcell-Cosmote NW.

Parameter	Default	Range	Unit	Setting for Turkcell	Setting for Cosmote
a1a2SearchThresholdRsrp	-134	-140 to -44	dBm	-94	-90
a5Threshold1Rsrp	-140	-140 to -44	dBm	-94	-90
a5Threshold2Rsrp	-136	-140 to -44	dBm	-96	-100
hysteresisA5	10	0 to 150	0,1 dB	10	10
timeToTriggerA5	640	0,40,64,80,100,128,160,256,320,480,512,640,1024,1280,2560,5120	msec	640	640

Figure 58: Event A5 and parameter default and set values

Mobility Control at Poor Coverage (MCPC) builds on the legacy Session Continuity features to provide more control over mobility when poor coverage is encountered.

When in the search zone(s), the UE searches for good enough coverage from other frequencies, potentially both intra/inter-frequency LTE (using A3 (intra-Frequency) or A5 (inter-Frequency) measurements). Without this feature, blind and measurement-based release to different targets is not possible. Handover location can be tuned using a1a2SearchThresholdRsrp / a5Threshold1Rsrp / a5Threshold2Rsrp / hysteresisA5 / timeToTriggerA5 parameters. Quality based parameters are also available for the tuning process (a1a2SearchThresholdRsrq / a5Threshold1Rsrq / a5Threshold2Rsrq). In 5G-Mobix project signal level based thresholds have been used.

- LTE-NR downlink and Uplink carrier aggregation related parameters:
    - dcScellActDeactDataThres: -1, Minimum time is calculated as number of bits in all priority queues, divided by number of bits that can be transmitted in one TTI by all active serving cells (prior to activation decision). Computed as if UE is given all resources in those cells. If condition for activating one Scell is satisfied, a second Scell is also considered for activation. Minimum time needed to transmit all bits is now re-calculated with added capacity of new Scell. Another Scell is added if still over threshold. "-1" means data-triggered activation condition is always satisfied even with no data in buffer, and also that data-triggered deactivation condition is never satisfied.
    - scellDeactProhibitTimer: 5000, Deactivation prohibit timer. No new Scell deactivation is allowed while this timer is running. "5000 ms" is maximum duration.

Below Figure 59 is illustrating how LTE-NR Downlink and Uplink CA parameters are working.

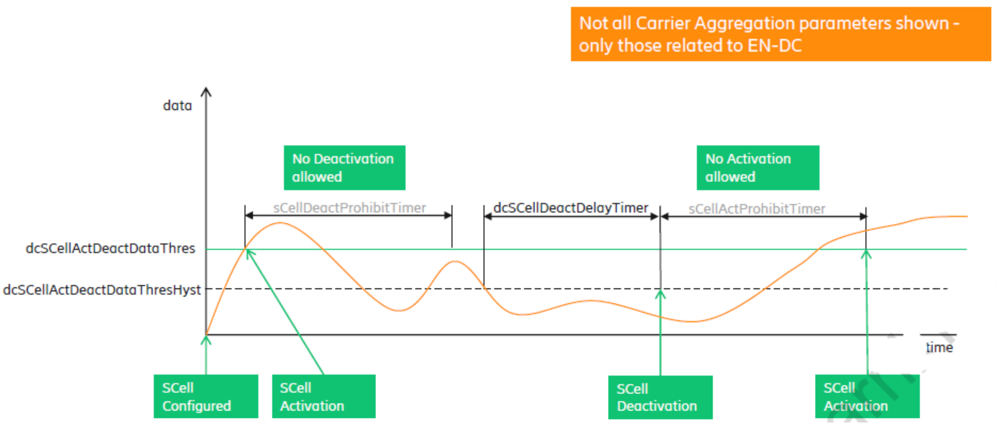


Figure 59: LTE-NR Downlink and Uplink CA parameters working mechanism

The Figure 60 below shows the default and set values of the LTE-NR Downlink and Uplink CA parameters parameter in Turkcell-Cosmote NW.

Parameter	Default	Range	Unit	Setting for Turkcell	Setting for Cosmote
dcScellActDeactDataThres	100	-1, 0 to 5000	0.1 Number of DL subframes	-1	-1
scellDeactProhibitTimer	200	0 to 5000	msec	5000	5000

Figure 60: LTE-NR Downlink and Uplink CA parameter default and set values

At the GR side, the commercially employed TDD pattern is used. This TDD frame is considered DDDSUUDDDD (3:8:3) for the CAM user cases where good coverage, demanding uplink. At the TR side, the same TDD frame has been used to align with GR network and minimize interference that could lead to service disruption.

TDD Pattern	Status
DDSU (11:3:0) (3DL + 1UL)	Default
DDDSUUDDDD (3:8:3) (4DL+2UL+4DL)	Used Config
DDDSUUDDDD (4:6:4) (4DL+2UL+4DL)	
DDDSUUDDDD (6:4:4) (4DL+2UL+4DL)	
DDSSUUDDDD {6:8:0, 0:10:4} (4DL+2UL+4DL)	
DDDSU (10:2:2) (4DL+1UL)	
DDDSU (11:3:0) (4DL+1UL)	
DDDSUDDSUU (10:2:2) (4DL + 1UL + 3DL + 2UL)	
DDDSUDDSUU (11:3:0) (4DL + 1UL + 3DL + 2UL)	
DDDDDDDSUU (6:4:4) (8DL+2UL)	

Figure 61: TDD patterns for NR

In Figure 61, available TDD patterns are shown for NR. During project deployment phase, additional TDD patterns have been tested.

- Allow UEs to transmit more UL power using pZeroNomPuschGrant and pZeroNomPucch parameters. These changes may increase UL interference, but at the same time increase UL throughput performance. Configuring the following attributes in the cell affects the maximum RF output power:
    - pZeroNomPuschGrant used for Power control parameter Po Nominal for PUSCH transmissions with grant.
    - pZeroNomPucch used for Power control parameter Po Nominal for PUCCH transmissions.

The Figure 62 below shows the default and set values of the pZeroNomPuschGrant and pZeroNomPucch parameters in the Turkcell-Cosmote NWs.

Parameter	Default	Range	Unit	Setting for Turkcell	Setting for Cosmote
pZeroNomPuschGrant	-100	-202 to 24	dbm	-98	-98
pZeroNomPucch	-114	-202 to 24	dbm	-112	-112

Figure 62: pZeroNomPuschGrant and pZeroNomPucch params

5.4.3 *Transport Upgrades – TR side*

In terms of transport network, some capacity upgrades were made by TR side, while also some MW links were substituted by fibre, ever since the fibre connectivity works were carried out in the areas of interest. Specifically, the “IPSLA” station has been included in the CTAN ring and has 10G capacity ready. In terms of “EDIPY” site, which is at the Turkish custom place, initially, its MW link capacity was 1+0 – 400Mb and was increased to 2G with XPIC work while the link “EDIPY-IPSLA” was put into service. Later, with the completion of fiber preparations, MW link was disabled, and services were transferred to fiber. In addition, in terms of “EDIPS” site, the MW link capacity of 1+0 – 400Mb was increased to 1.2G with the XPIC work and “EDIPS-IPSLA” link was put into service. At the same time, work has been completed for TN soft configurations in TM_TAN (Collection Center for Many Sites and Transport Point for Them), NDC, UPE, APE and NPE layers.

5.5 GR-TR Verification Results

All four user stories carried out in the GR-TR cross-border corridor have been thoroughly tested and their functionality has been verified through a multitude of tests as reported in Deliverable D3.6 [34]. Specifically, the GR-TR partners applied contingency plans, and performed multiple verification tests remotely, which entailed the integration of OBUs, RSUs and applications developed by different partners, with the FORD truck and with remote servers. The results of these tests were reported in D3.6 [34]. In this deliverable, the results of the final verification of the proper functionality of the various components and their integration with the 5G network are reported. Table 36 provides the overview of the status of the verification tests of all four user Stories implemented in the GR-TR CBC.

Table 36: Final verification results for the GR-TR CBC

User Story	Pass	Fail	Partly	Not tested	Completion %
"See what I see" functionality in cross-border settings	33	0	0	0	100%
Platooning through 5G connectivity	27	0	0	5	84%
Extended sensors for assisted border-crossing	49	0	0	0	100%
Truck routing in customs area	29	0	2	4	86%

More specifically for each of the User stories:

- **<u>"See what I see" functionality in cross-border settings</u>**: In verification terms, this user story was successfully completed (100%). The relevant tests included the full functionality of application devices (server and client devices) and their modules adaptation to what the project needed. The application server was successfully established in Alexandroupoli premises while the client devices were successfully connected and integrated with the IMEC OBUs in Ford trucks. During further tests in the border area the application's functionality while the trucks cross the GR-TR borders was efficiently tested completing that way the verification process. The full verification checklist is available at the project repository.
- **<u>Platooning through 5G connectivity</u>**: Application developments of this user story completed and successfully tested in local trial site Eskişehir (Ford Otosan Plant, test facilities) and also in İpsala, GR-TR border crossing area. Two trucks used for this user story and each truck has IMEC OBUs to communicate with Turkcell 5G-Platooning Server via 5G and MQTT protocol. Turkcell server has MQTT Broker and IMEC OBUs have MQTT Client software to accomplish message exchange between trucks and Turkcell server. All connection tests also performed without any problem. Trucks followed each other with 1.5 second time gap with 5G connection. During the tests, logging issue were faced with DEKRA Tool. Root cause of issue was Dekra Tool agent application settings and missing software that needs to be installed to collect data from agents. All issues are solved but logging run couldn't be completed, due to trial time in border area was limited. Data logging is completed before 9th of May, GR-TR Demo Day and completion of the user story is 100%.
- **<u>Extended sensors for assisted border-crossing</u>**: This user story successfully completed 100% of the envisioned verification tests, which included the communication of the OBU and RSU with three servers (cloud server in Athens, edge server in Alexandroupoli and edge server at Istanbul). During the tests several bugs were found and corrected, and all functions of the user story have been verified. The full verification checklist is available at the project repository.
- **<u>Truck routing in customs area</u>:** This user story was successfully tested and verified in terms of functionality. Autonomous Truck Routing application was successfully deployed on TUBITAK Cloud in Kocaeli. The application was connected to the IMEC OBUs in the Ford truck and integrated. Also, IMEC RSUs were placed on the customs area and their connection and integration with the cloud application was verified. Autonomous driving of the truck was enabled by processing precise location information from OBU and LiDAR data from RSUs. Encountered issues were solved during the tests and all functions of the scenario were verified. However, logging part of the verification could not be completed yet. Due to the security measures in the cloud's firewall, the DEKRA tool we use for logging encounter connectivity issues. The full verification checklist is available at the project repository.

5.5.1 Radio Network testing framework

Network tests are very important for the use cases to work correctly. For this purpose, many test cases were carried out during the network verifications. Some information about these tests is given below.

5G-MOBIX - D3.7_Appendix-Results_GR-TR - (sharepoint.com)

After the physical and parametric optimization work was completed, all sites were tested individually. These tests are within the scope of the agnostic tests.

After individual tests had been completed, Intra PLMN mobility tests were carried out on the Turkish side, while, Inter PLMN tests, including Turkcell and Cosmote networks, were also carried out. During that period Ericsson, Turkcell and Cosmote engineers worked together.

Before analysing the test results, information about the test environment on the border of Greece and Turkey should be provided. Three of the four sites in total are located on the Turkish side. Since all of these sites are located on the tower, the control of the radio signals has created a significant difficulty. The Cosmote site, which provides service to the border region, is further away from the Turkcell site. For this reason, it shows poor performance in some areas on the test route. Figure 63 is illustrating a general view of the GR-TR corridor.

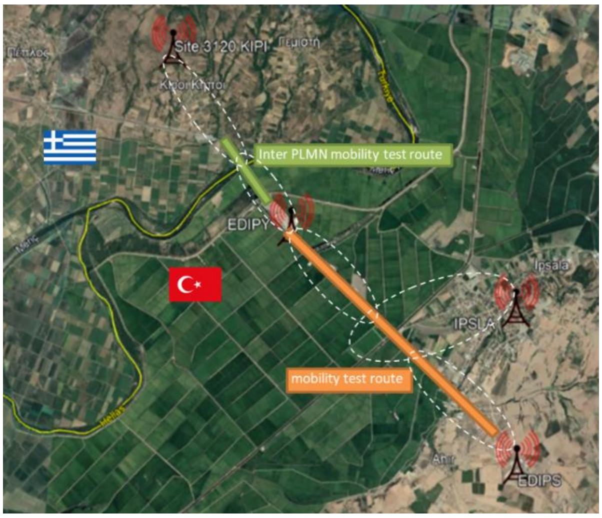


Figure 63: General view of the GR-TR corridor

Since the UEs used during the agnostic tests were inside the vehicle, some problems were experienced in the signal levels. In addition, the use of metal fences close to the custom area had an impact on the heavy truck traffic test results. In Figure 64, Inter PLMN test environment of the GR-TR corridor is depicted.

Figure 64: General view of the GR-TR corridor - 2

5.5.2 Network testing and verification results

Many tests were carried out during the project. All details of the tests can be accessed from the link [5G-MOBIX - D3.7_Appendix-Results_GR-TR - (sharepoint.com)](). Mobility is essential of the wireless telecommunication. In NSA networks some of the necessary signalling procedures must be followed. In EN-DC (EUTRA NR Dual Connectivity), LTE would become an MCG (Master Cell Group) and NR would become a SCG (Secondary Cell Group). MCG works as the anchor and UE performs initial registration to this anchor cell group, and this anchor cell add one or more Secondary Cells (SCG).

In the following section, there is information about how the Intra and Inter PLMN HO mechanism works, and the results of the measurements made.

5.5.3 Intra PLMN Handover Test

In the following scenario, "Inter-MeNB handover without SgNB change triggered by MeNB" analysed. Test setup is shown in below Figure 65. This case is related to Intra PLMN HO mobility and focus mobility interruption time KPI. During the test, LTE and NR sectors belonging to EDIPS (PCI:463) site and LTE sector belonging to IPSLA (PCI:202) site was activated.

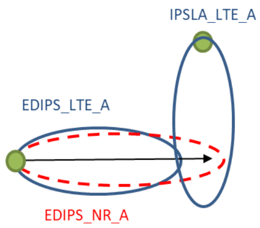


Figure 65: Inter-MeNB handover without SgNB change triggered by MeNB test setup

The test started from the service area of the EDIPS site and UE moved to the IPSLA site. Base Band traces were taken from EDIPS and IPSLA sites.

The HO procedure takes place in two different stages.

- Step1: LTE-LTE Handover (EDIPS_LTE_A to IPSLA_LTE_A) and MeNB initiated SN Leg release (EDIPS_LTE_A released to EDIPS_NR_A)
- Step2: SN Leg addition on new MeNB (IPSLA_LTE_A added EDIPS_NR_A as a SCG)

During the Handover 63ms data transmission has suspended on LTE leg (UE-X2AP-IDs also can follow between transitions in Figure 65). In this period UE cannot set-receive any data. LTE interruption has calculated as time difference between "RRCConnectonReconfiguration" message sent by source LTE cell and "RRCConnectonReconfigurationComplete" message received by target LTE cell.

LTE mobility also initiates the NR leg removal and insertion procedure. During SN leg deletion and addition procedure data transmission suspended on NR leg at the same time with LTE leg. According to below calculation MeNB initiated SN release and addition procedure takes 478msec. NR interruption has calculated as; time difference between "SgnbReleaseRequestAcknowledge" message sent by SgNB to MeNB and "E-RABModificationConfirm" message sent by MME to MeNB.

Detailed information about this analysis can be found in the file 5G-MOBIX – GR-TR_Agnostic_Test_Results_Final.xlsx in the sheet TCA-GEN-25. The report can be accessed via the link: D3.7_Appendix-Results_GR-TR. Results of other analyses can also be accessed in the same report as,

- Intra MeNB mobility MeNB same - SgNB different, Sheet: TCA-GEN-24
- Inter MeNB mobility no SgNB, Sheet: TCA-GEN-26

During the Intra PLMN HO tests, B1 measurement based SCG addition procedure has been used. In this way, with multiple NR leg availability best performing one was chosen by the UE. For this reason, the SCG deletion-addition procedure lasted more than LTE interruption time. In the Inter PLMN tests "Blind-Configuration based HO" procedure was applied (Blind- Configuration based HO: independent of B1 measurement, adding NR leg automatically when LTE makes HO and NR leg available). The aim is here, to add NR leg as much as faster after LTE handover. Because there is not any other NR leg available for adding as SgNB.

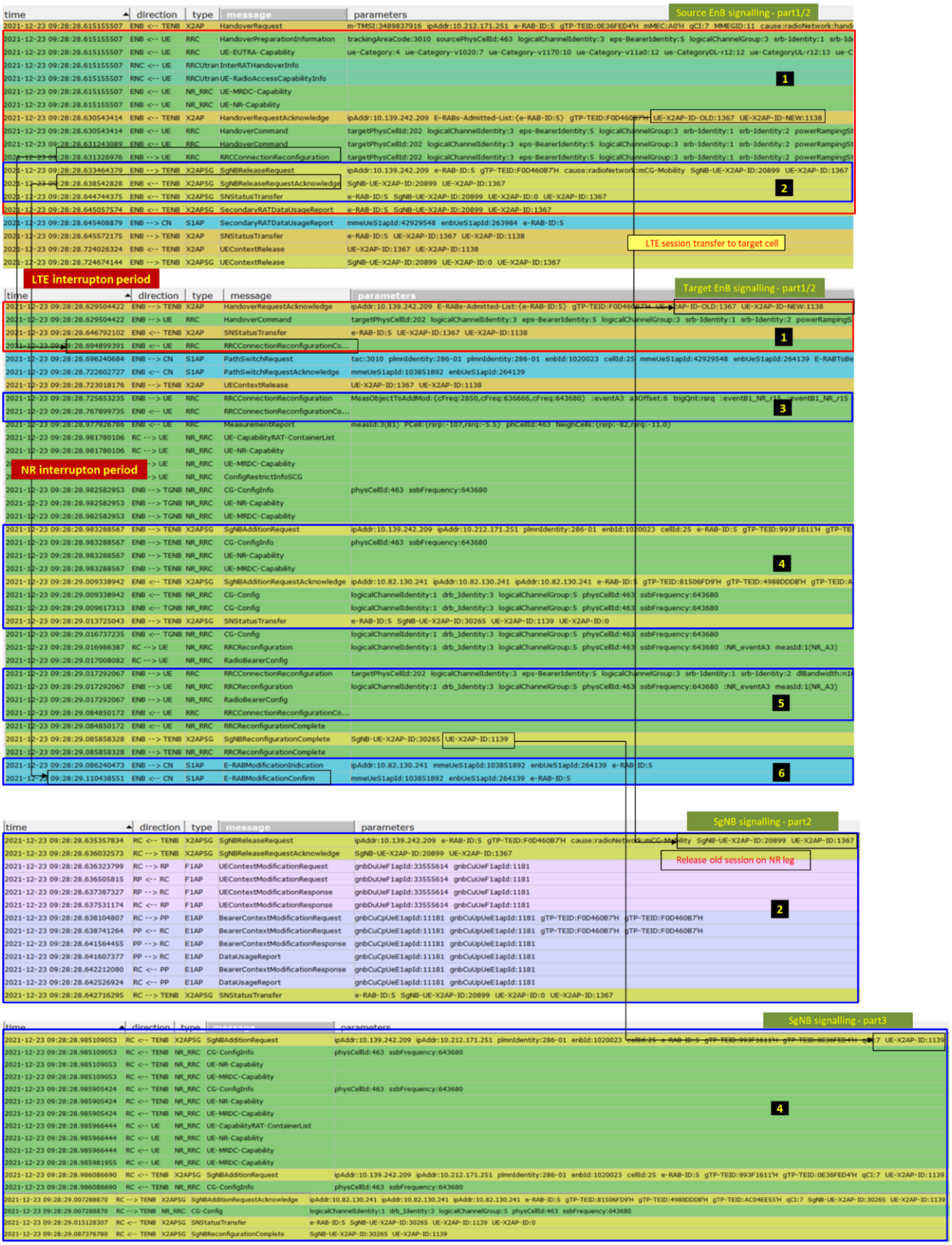


Figure 66: Inter-MeNB handover without SgNB change triggered by MeNB

5.5.4 Inter PLMN Handover Test

The handover process triggering by MeNB is the same as all NSA networks and SgNB adding without B1 measurement (Blind HO process is followed here). The test setup is shown in Figure 67 below. During the test, LTE-NR sectors belonging to EDIPY (PCI:175) and KIPOI (PCI:102) sites were used.

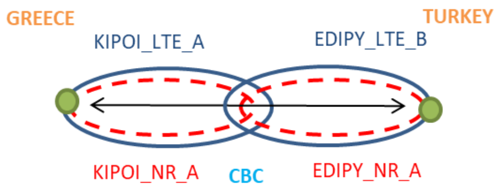


Figure 67: Inter PLMN Handover test setup

Unlike the case Intra PLMN Handover, mobility interruption time measurement was made with the help of trace information obtained from home and visited MMEs. Traces were started at the same time before the test. The entire signalling flow is shown in the Figure 68.

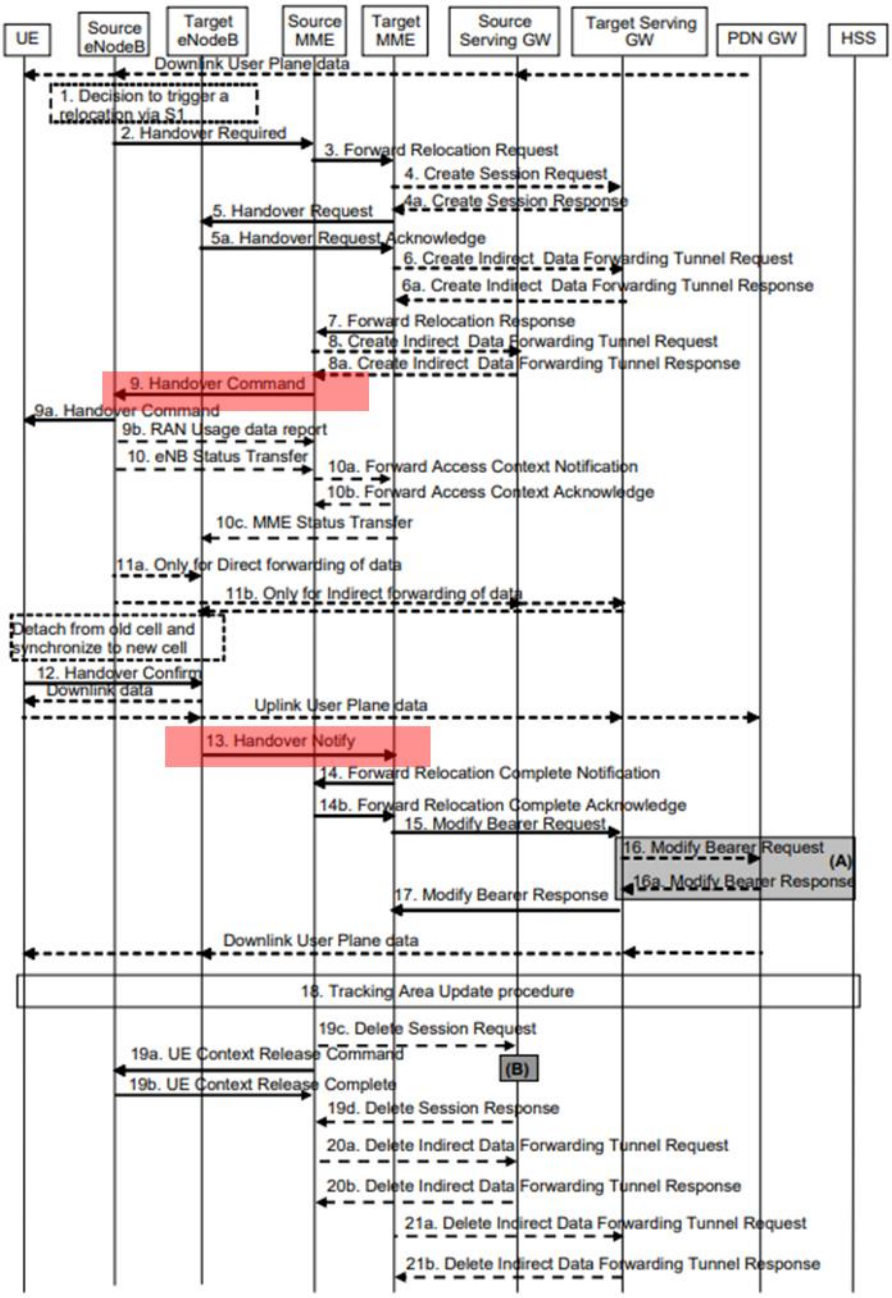


Figure 68: Inter MME Handover signaling flow (3GPP TS 23.401)

In the Table 37, the Source and Target MME trace info are shown in the time domain. User data is suspended after the "HandoverCommand" message is sent from "Source by MME" to "Source eNodeB" (Message 9). "RRCConnectionReconfigurationRequest" message is sent after this message which is not displayed in the signalling flow. After "HandoverNotify" message is sent from "Target EnB" to "Target MME" (Message 13), user data transmission resumes. "RRCConnectionReconfigurationComplete" message that comes before that message is not displayed in the signalling flow. In this example downlink user data interruption time was calculated as 82ms. Below messaging flow contains only the details related to LTE. Detailed analysis can be found in the report 5G-MOBIX – GR-TR_Agnostic_Test_Results_Final.xlsx file Sheet: TCA-GR-TR-06_InterPLMN_HO_HR at Test1_TCP_DL TurkcellSIM-Turkcell Edge Server test scenario. The report can be accessed with the following link: D3.7_Appendix-Results_GR-TR.

Table 37: Final verification results for the GR-TR CBC

Message No	SOURCE MME : Turkcell MME
	TR to GR
2	12:03:52,083 eNodeB -> MME S1 S1AP Handover required
3	12:03:52,084 MME <- MME S10 GTPv2-C Forward relocation request
7	12:03:52,204 MME <- MME S10 GTPv2-C Forward relocation response
9	12:03:52,204 eNodeB <- MME S1 S1AP Handover command
	12:03:52,237 eNodeB -> MME S1 S1AP Secondary RAT Data Usage Report
10	12:03:52,238 eNodeB -> MME S1 S1AP eNB status transfer
10a	12:03:52,238 MME <- MME S10 GTPv2-C Forward access context notification
10b	12:03:52,313 MME <- MME S10 GTPv2-C Forward access context acknowledge
14	12:03:52,322 MME <- SGSN_MME S3_S10 GTPv2-C Forward relocation complete notification
14b	12:03:52,322 MME <- MME S10 GTPv2-C Forward relocation complete acknowledge
	12:03:52,703 MME <- HSS S6a Diameter Cancel location request
	12:03:52,703 MME -> HSS S6a Diameter Cancel location answer
19a	12:03:52,703 eNodeB <- MME S1 S1AP UE context release command
	12:03:52,703 MME -> SGW S11 GTPv2-C Delete session request
	12:03:52,709 MME <- SGW S11 GTPv2-C Delete session response

Message No	TARGET MME : Cosmote MME
	TR to GR
3	12:03:52,134 MME <- MME S10 GTPv2-C Forward relocation request
4	12:03:52,137 MME -> SGW S11 GTPv2-C Create session request
4a	12:03:52,139 MME <- SGW S11 GTPv2-C Create session response
5	12:03:52,139 eNodeB <- MME S1 S1AP Handover request
5a	12:03:52,168 eNodeB -> MME S1 S1AP Handover request acknowledge
7	12:03:52,168 MME <- MME S10 GTPv2-C Forward relocation response
10a	12:03:52,278 MME <- MME S10 GTPv2-C Forward access context notification
10b	12:03:52,278 MME <- MME S10 GTPv2-C Forward access context acknowledge
10c	12:03:52,278 eNodeB <- MME S1 S1AP MME status transfer
13	12:03:52,286 eNodeB -> MME S1 S1AP Handover notify
14	12:03:52,286 MME <- MME S10 GTPv2-C Forward relocation complete notification
14b	12:03:52,362 MME <- MME S10 GTPv2-C Forward relocation complete acknowledge
15	12:03:52,362 MME -> SGW S11 GTPv2-C Modify bearer request
	12:03:52,415 eNodeB -> MME S1 S1AP E-RAB modification indication
17	12:03:52,440 MME <- SGW S11 GTPv2-C Modify bearer response
	12:03:52,441 MME -> SGW S11 GTPv2-C Modify bearer request
	12:03:52,443 MME <- SGW S11 GTPv2-C Modify bearer response
	12:03:52,443 eNodeB <- MME S1 S1AP E-RAB modification confirm
	12:03:52,612 eNodeB -> MME S1 S1AP Uplink NAS transport
	12:03:52,612 UE -> MME S1 NAS Tracking area update request
	12:03:52,613 MME -> HSS S6a Diameter Update location request
	12:03:52,752 MME <- HSS S6a Diameter Update location answer
	12:03:52,754 UE <- MME S1 NAS Tracking area update accept
	12:03:52,754 eNodeB <- MME S1 S1AP Downlink NAS transport
	12:03:52,806 eNodeB -> MME S1 S1AP Uplink NAS transport
	12:03:52,806 UE -> MME S1 NAS Tracking area update complete
	12:03:52,806 UE <- MME S1 NAS EMM information
	12:03:52,806 eNodeB <- MME S1 S1AP Downlink NAS transport
	12:03:52,807 MME -> HSS S6a Diameter Authentication information request
	12:03:52,944 MME <- HSS S6a Diameter Authentication information answer

Trace methods are generally used in problem analysis. Data collection and analysis are time-consuming processes. The aim here is to understand how close it is to the values measured with drive test. According to the measurement results, very close values have been reached. For this reason, drive test method was used for the rest of the tests.

5.6 GR-TR Deployment Challenges & Lessons Learned

The GR-TR cross-border corridor faced various deployment challenges, technical and non-technical ones, as the only corridor involved in 5G-MOBIX project with hard borders. The encountered challenges, accompanied with useful insights and lessons, are summarised below.

5.6.1 Physical implementation issues

Physical implementation issues were encountered during field tests. In the 5G-Mobix project, MNOs commercial LTE network antennas are used as NR anchoring for both networks. Some physical adjustments had to be made since there was an overshoot to undesirable places. In addition, given that the area served by commercial antennas and the service areas needed in the 5G-Mobix project do not overlap, the LTE antenna needed for NR anchoring was separated from the commercial network and a different antenna was used.

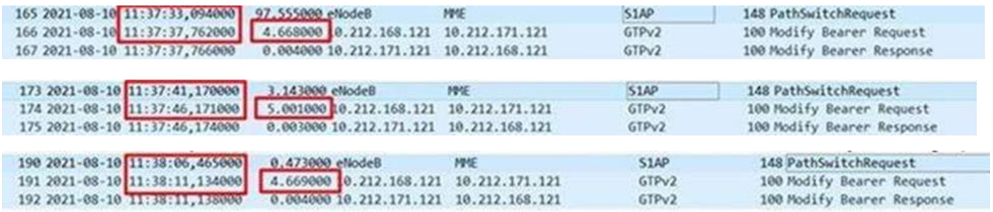
According to commercial network needs, sites were established as 3 or 4 sectors, while the sites in Turkcell within the scope of the 5G-Mobix project are planned as 2 sectors. During the installation of these sites, the sector numbers were mixed, and the connection was made according to the commercial network sector numbers. It has been determined during the tests that with this mounting method, the sectors serve in different directions, not the desired direction. After the correction made, service started to be received in the required region.

5.6.2 Optimisation activities and configuration challenges

After physical implementation activities have been done, fine-tuning and radio parameters' optimisation activities took place focusing on avoiding ping-pong effects and possible interference, while ensuring seamless handover at border area. For such activities, strong collaboration between both sides of the border is required. Specifically, section 5.4.2 Parameter Optimization describes in detail those radio parameters that had to be mutually agreed between two MNOs and correctly set in order to achieve fine-tuned networks at the cross-border area.

Apart from radio optimization activities, an end-to-end fine-tuned network is required. During the tests, it was determined that there was an interruption of 5 seconds in every handover between sectors belonging to different sites. After in depth investigation, it was realized that the problem was caused by a parameter in the Core Network.

Specifically, during mobility procedure eNB sent pathSwichRequest to MME. However, MME did not respond in the required time frame. After an internal MME timer expired in 5sec the connection was released and re-established again. The following Figure 69 is illustrating the service interruption problem.



165	2021-08-10	11:37:33,094000	97.555000	eNodeB	MME	S1AP	148	PathSwitchRequest
166	2021-08-10	11:37:37,762000	4.668000	10.212.168.121	10.212.171.121	GTPv2	100	Modify Bearer Request
167	2021-08-10	11:37:37,766000	0.004000	10.212.171.121	10.212.168.121	GTPv2	100	Modify Bearer Response
173	2021-08-10	11:37:41,170000	3.143000	eNodeB	MME	S1AP	148	PathSwitchRequest
174	2021-08-10	11:37:46,171000	5.001000	10.212.168.121	10.212.171.121	GTPv2	100	Modify Bearer Request
175	2021-08-10	11:37:46,174000	0.003000	10.212.171.121	10.212.168.121	GTPv2	100	Modify Bearer Response
190	2021-08-10	11:38:06,465000	0.473000	eNodeB	MME	S1AP	148	PathSwitchRequest
191	2021-08-10	11:38:11,134000	4.669000	10.212.168.121	10.212.171.121	GTPv2	100	Modify Bearer Request
192	2021-08-10	11:38:11,138000	0.004000	10.212.171.121	10.212.168.121	GTPv2	100	Modify Bearer Response

Figure 69: Core NW signaling log

The issue has been solved after correcting ncl (NetworkCapabilityList) set to NR. Figure 70 is depicting the network performance before and after correction. From the above, it is obvious that any missing configuration effect NW performance directly.

Figure 70: Core NW signaling - correction

5.6.3 Direct cross-network interconnection via dedicated leased line

Turkcell and Cosmote networks, like all other MNOs supporting roaming, are currently interconnected through IPX/GRX network so that subscribers of both MNOs can obtain services from the visited network and related roaming traffic traverses through IPX/GRX networks, which are optimum designed for traditional services (i.e. voice, data) with exchange hubs deployed at specific main geographical locations. However, in order to fulfil the strict latency requirements imposed by the CAM use cases supported at the GR-TR cross-border trials, it was decided that the networks of Cosmote and Turkcell would be interconnected directly via a leased line. Indeed, the direct interconnection between operators reduced the latency of the messages exchanged during inter-PLMN handover between the two distributed edge cores, which are close to the borders, compared to making use of IPX/GRX networks that have a centralized architecture approach.

From the above, it is obvious that for efficient CAM messages exchange in border countries, direct interconnection of the involved networks via dedicated lines is required. Currently, dedicated lines between operators do not exist and should be implemented following the optimum transmission path in terms of length and cost.

5.6.4 Other Non-Technical Challenges

Taking into account the special characteristics of the GR-TR CBC, which is the south-eastern border of the European Union and the only corridor in the project with a hard border, specific non-technical challenges were encountered as described below.

- Since Turkey is not a member of the European Union, project workers are required to obtain a visa at border crossings. Issuing of a visa is a time-consuming procedure and Visa applications should have been made quite in advance.
- Delays at border crossings are inevitable, not only due to the Covid-19 pandemic, but also due to the corridor's important and intensive use in terms of commercial transportation.
- While the project tests are being conducted, the police and military authorities must be informed before the border crossing. The authorities in the project organization have made great efforts on the subject and have helped to solve many problems. However, although these permits were obtained, a lot of time was lost during border crossings due to various coordination problems. The difficulty of carrying out such projects in high security areas was seen in this project.

The above-mentioned challenges that were faced during the 5G-MOBIX trial phase stress the need to take into consideration all possible non-technical factors (i.e. from regulatory to visa application procedures) in order to have a successful CAM service outside the harmonized environment of European Union.

5.6.5 GPS based positioning from UE for the VRU use case

In order to perform the Vulnerable Road User (VRU) protection use case, the location of the custom's agent holding the smartphone (UE) has to be known. An initial challenge was that the GPS coordinates could not be received at the application layer through commercial GPS applications (e.g., Google maps) since the 5G test network used at the GR-TR CBC does not provide open access to the public internet for security reasons. Only IP whitelisting works, but the IPs of such global services are never exactly known. This challenge was resolved by designing and using a custom GPS coordinates retrieving application which was installed in the used UEs, and which transmitted the coordinates to the desired application server.

Another challenge was the fact that the refresh rate of commercial GPS equipment and UEs, is about 1 Hz (best case scenario), which means it is not sensitive to quick changes and not suitable for CAM use cases, while at the same time the accuracy of the coordinates is not great (> 1.5 meters). To overcome this challenge, the VRU protection algorithm was re-designed to fuse information from the GPS receivers of the truck and the UE of the custom's agent with information form the proximity sensor mounted in the front of the truck. This sort of "double factor verification" with regards to the detection of a VRU in front of the truck, increased the detection accuracy and allowed the use case to be performed optimally.

5.6.6 Significant signal attenuation at the OBU with internal antennas

The initial version of the OBUs designed and used in the GR-TR CBC, used internal antennas. After the first field tests it became obvious that the Received Signal Strength (RSS) at the OBUs was significantly affected by the wind-shield and windows of the truck, and as such was much lower than what was experienced with other devices when measuring in the open space. To address this issue, and to provide the best performance possible, all OBUs used in the GR-TR corridor were retro-fitted with cable extensions in order to use external antennas mounted on top of the truck. This upgrade immediately improved the experienced performance and allowed for the successful execution of the GR-TR User Stories.

6. DE TS DEVELOPMENT, INTEGRATION & ROLL-OUT

6.1 Site Overview

The German trial site is located in the city centre of Berlin and comprises two use cases, namely eRSU assisted Platooning and EDM-enabled extended sensors with surround view generation. The Berlin corridor is situated in the centre of Berlin, Straße des 17. Juni and it is a 4 km long road extending from Ernst-Reuter-Platz to Brandenburger Gate. This is an urban corridor with three lanes in each direction, two complex roundabouts (with 5 roads and multiple lanes), and a high traffic intensity during working hours. The very dense driving environment of the Berlin corridor, having a rich amount of digitized street infrastructure and different types of sensors, provides ideal testing capabilities for the various use case categories of automated driving in especially borders exhibiting heavy and heterogeneous traffic. Due to the urban setting of the Berlin test field with real road traffic, the trials at the DE TS were always conducted with a human driver in control of the vehicle. This enabled continuous testing of 5G for CAM functionalities without requiring road closures or other regulatory restrictions.

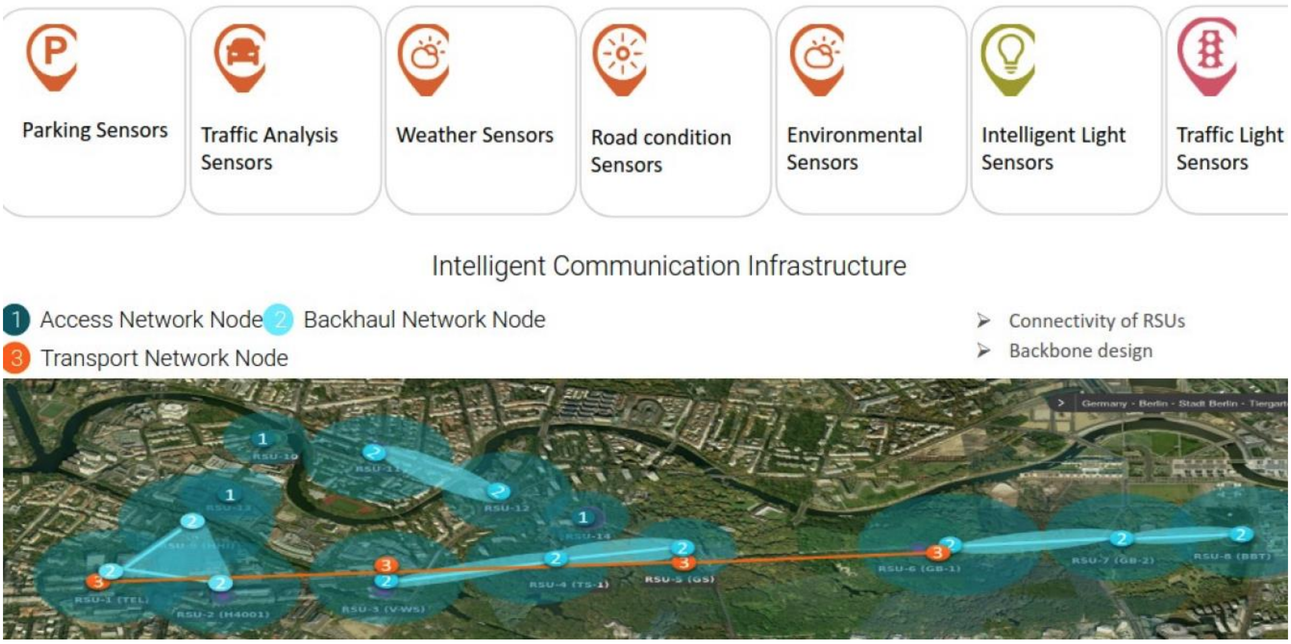


Figure 71: DE TS Berlin corridor overview

To create the EDM-Service, the DE TS roadside infrastructure features in total nine extended roadside units (eRSU), which have been deployed along the digitized road stretch to provide extended perception to vehicles as shown in Figure 71. Furthermore, to enable the evaluation of CAM use cases, the DE-TS has also access to two different 5G network deployments. For this reason, the UEs employed in the use cases could change from one network to another, allowing for the assessment of the performance of experiments in the context of an "emulated roaming" scenario. We simulated a border crossing between two countries regarding cellular connectivity. The vehicles move across the 5G coverage areas of two different MNOs while remaining in the same city. In this context, the focus is not on a handover from one base station to another of the same operator. Instead, the UE leaves the coverage area of one operator and then attaches to the other operator to establish a new data connection on the other network.

6.2 DE Deployed Components

6.2.1 Overview of the deployed components

Table 38: DE TS Overview of deployed components

5G Networks										
Operator & vendor	***NSA/ SA***	**Num. gNBs**	**Freq. Bands**	**BW**	**TDD Frames**	**Network Sync**	**Backhaul**	**Core attributes**	**Core interconnect**	**Key HO / roaming param.**
DT	NSA	10-15	Full covered TS: 2.1 GHz (5G NR n1) + 800 MHz (LTE B20), 900 MHz (LTE B8), 1800MHz (LTE B3) anchor bands Partial coverage TS: 3.6 GHz (5GNR n78) + 1800MHz (LTE B3), 2600 MHz (LTE B7) anchor bands	N/A	N/A	Time and Phase	>100GHz Fiber	CRAN vs DRAN, Fronthaul,etc	DTE-Vehicle	N/A
TUB Campus	SA	1	3.7 - 3.8 GHz (5G NR n78)			Time and Phase	Fiber		TUB Cloud-Vehicle	
5G Features / Technologies / Configurations addressed										
(e.g., Home-Routing, Local Break-out, S1 base HO, S10 based HO, Direct line, SA slicing, Uu / PC5 communication, MEC/Edge based operation, Cloud based operation, multi-SIM, mmW etc.)										

Vehicles & On-Board Units															
Vehic		**Type**	**Make & model**	**SAE Level**	**Vehicle Sensors**	**Vehicle capabilities / functions**	**OBUs**		**Developer / Vendor**	**Num. OBUs**	**Num. SI**	**OS**	**Sup. Mode**	**5G Chipset / Modem**	**OBU sensors**

l e s											M s				
	Vehicle 1	Passenger Car	VW Tiguan	3	GPS, camera, LiDAR, RaDAR, ultrasonic, etc.	Platooning & Extended Sensor Applications		**OBU 1**	Valeo Peiker and MK5 (DSRC) & MK6c(PC5) by Cohda Wireless	2	2	Linux	V2X	Valeo Vulcano 2.0 TCU RG500Q-EA CS2 Qualcomm MDM 9150 C-V2X chipset	GNSS
	Vehicle 2	Passenger Car	VW Passat Variant	3	GPS, camera, LiDAR, RaDAR, ultrasonic, etc.	Platooning & Extended Sensor Applications		**OBU 2**	Valeo Peiker and MK6c (PC5) by Cohda Wireless	4	1	Linux	V2X	Valeo Vulcano 2.0 TCU RG500Q-EA CS2 Qualcomm MDM 9150 C-V2X chipset	GNSS

Roadside & Other Infrastructure

MEC / Edge nodes	Num. Cloud instances	Num. RSUs	Num. ITS centers	Applications / User Stories	Message type	Supported interface	Supported protocols / APIs	Road side sensors	Supported mechanisms / Features
eRSU (MK6C (PC5), MK5 (DSRC) & Quectel 5G modem)	1 Mobiledge X	14	1 DAI Data Center	e-RSU assisted platooning, extended sensors	CAMes, DENM, CPM, BSM, WSA, RSA	UU & PC5	ITS, MQTT, Kafka, WebRTC	Camera, weather, road park, humidity	V2X/ Edge interconnection, local breakout, geolocation

6.2.2 Measurement Framework

In the DE TS, different tools have been used, depending on the test type. For the agnostic test cases, mainly tools from DEKRA have been used. For the specific test cases, also custom python application and other Linux tools were also needed. There tools are specified in Table 39:

Table 39: DE TS Measurement Tools

Measurement tools used in DE TS		
Tool Name	**Attributes**	**Details**
DEKRA Performance Tool TACS4-Mobile App	Testing platform used for evaluation of performance and user experience in cellular and wireless networks	This is a commercial tool used for all the common agnostic tests: KPI_AG1 to KPI_AG9
	PCO Level 0 and 1	PCO Level 0 and PCO Level 1
	OBU, MEC, RSU, ITS cloud	The PCOs used by the tool in the agonistic tests conducted in the DE-TS are OBU, MEC, RSU and ITS cloud
	Traffic injection	ICMP, TCP and UDP traffic
DEKRA Performance Tool TACS4-Controller	Physical and network metrics	This is a commercial tool used in the specific testing of the UCC2/US2 and UCC3/US2
	PCO Level 0 and 1	PCO Level 0 and PCO Level 1
	OBU, MEC, RSU, ITS cloud	The PCOs used by the tool in the specific tests conducted in the DE-TS are OBU, MEC, RSU and ITS cloud
	N/A	N/A
Wireshark and Python	Wireshark: capturing and analysing PC5 packets. Python: Application level metrics	Wireshark is an open-source used to capture data packets and it is used in combination with a python script for post-processing in the specific testing of the UCC2/US2 to evaluate the communication via PC5 interface
	PCO Level 1 and PCO level 2	PCO Level 1 and PCO level 2
	OBU and RSU	The PCOs used by the tool in the specific tests conducted in the DE-TS are OBU and RSU

<table>
<tr><td rowspan="2">Quectel QLog</td><td>Capture the low level logs from Quectel Modems.</td><td colspan="2">All physical layer measurements regarding the 5G modems can be collected with this tool</td></tr>
<tr><td>PCO level 0</td><td colspan="2">PCO level 0 in the OBUs</td></tr>
<tr><th colspan="4">Time Synchronization approaches used in DE-TS for different entities</th></tr>
<tr><td colspan="2">Synchronised entities</td><td colspan="2">PTP master clock deployed in Cohda Mk6c units
PTP slaves deployed in the computers attached to the Mk6c (OBUs, RSUs)</td></tr>
<tr><td colspan="2">OBU ⇔ OBU
OBUs ⇔ RSUs</td><td colspan="2">PTP is used for synchronization between all OBUs and RSUs participating in the tests</td></tr>
<tr><td colspan="2">Measurement's accuracy</td><td colspan="2">< 1ms</td></tr>
<tr><td colspan="2">Measurements errors and correction techniques</td><td colspan="2">N/A</td></tr>
</table>

6.3 Updates During the Deployment process

The DE TS deployments have been reported in detail in the WP3 deliverables D3.2 [36], D3.3 [37]and D3.4 [33] that were initially released in early 2021 and, in case of D3.2 and D3.4, updated in their revised versions in 2022. The most important deployment update concerns the addition of TUB's own 5G SA gNB which was intended to be used also in for trials. The gNB has been installed successfully on the rooftop of the TUB VWS building in close vicinity of the DE TS track in August 2021, first (due to delayed availability of the planned server component) with a temporary x86 server for the gNB processing that had to be replaced later with the more powerful server hardware when it was delivered to TUB beginning of 2022. After the successful deployment of the gNB, the coverage area of the gNB was tested in field tests and turned out to not meet the expectations of providing stable coverage along the trial site track along Strasse d. 17. Juni from Tiergarten towards Großer Stern. Foliage and trees were obstructing the line of sight too much to allow for a stable connection to be established to the gNB while driving along the road. As a mitigation measure, the coverage area was adapted to point to the closer area in front of S-Bhf. Tiergarten. However, due to the special narrow sector antenna that was intended to cover the length of the road now only a small stretch of the road was covered by the 5G SA gNB which made drive tests for 5G-MOBIX trials somewhat infeasible. Instead of using the research gNB for trials, it was therefore decided to utilize O2 Telefonica 5G NSA network in addition to the commercial Deutsche Telekom 5G NSA for the DE TS trials. Agnostic test results for the gNB allow for comparisons among the different network deployments utilized in the DE TS.

6.4 DE Verification Results

In Table 40, the verification results for the DE TS are presented. In the Extended Sensors ES-PT CBC DE-TS Contribution verification tests, the handover was not performing correctly in the ES-PT CBC networks for all the configurations (ES-PT with ES SIM, PT-ES with ES SIM, ES-PT with NOS SIM, PT-ES with NOS SIM). That is why some verification tests here are marked as partly passed only.

Table 40: Final verification results for the DE TS

User Story	Pass	Fail	Partly	Not Tested	Completion
eRSU-assisted platooning	43	0	0	0	100%
EDM - Extended Sensors	39	0	0	0	100%
Extended Sensors US - ES-PT CBC DE-TS Contribution	33	0	5	0	93%

6.5 DE Deployment Challenges & Lessons Learned

The DE TS has faced some challenges and barriers during the development and deployment stages of 5G-MOBIX. The lessons learnt are presented in the following tables using a common template and classified in three categories:

- Technological
- Legal and regulatory
- Reliability and availability

The tables are structured using the following fields:

- Challenge: challenge title.
- Description: brief description of the challenge.
- Satisfied: is the challenge or requirement satisfied using current technology/conditions? (products, regulations, etc).
- Impact: impact on user stories of not satisfying the requirement or challenge.
- Workaround: workaround proposed by DE TS to mitigate the impact and carry on the trials.

6.5.1 Technological lessons learnt

In Table 41, the main challenges and their impact, together with the respective workarounds are described. As explained, some of the challenges were not overcome, normally due to network issues.

Table 41: DE TS technological lessons learnt

Challenge	Description	Satisfied	Impact	Workaround
Seamless Roaming	Instant Roaming between different MNOs means seamless communication for Apps and OS	No. Current networks do not support cross-border CAM services due to long disconnection times	Communications Blackout during seconds (After attaching to roaming network)	Dual Modem and MEC service to UEs for assisted roaming based on signal intensity and GPS positioning
Seamless Dual Modem inter-PLMN switch	The backup network interface is immediately running when one UE is disabled.	No.	The transition between UEs is not instant and Application system is temporally disconnected	Router that forwards traffic through one or other UE where both are enabled.

MEC discovery	UEs know the address of the MEC endpoint.	No. A MEC discovery service is required to be implemented in the application layer.	Vehicles do not know the address of the MEC and cannot connect to it.	MEC Registry deployed in the Cloud compiling available MECs. MEC Orchestrator deployed in each MEC to manage MEC Handover and data synch.
UE Intra-MNO IP visibility	UEs at the same area for the same MNO can communicate with each other though UDP sockets	Sometimes, depending on the MNO.	Big latencies and lower scalability	Internet Server Gateway
UE Inter-MNO IP visibility	UEs at the same area for different MNOs can communicate each other though UDP sockets	No	Big latencies and lower scalability	Gateway installed on a server and publicly available in Internet.
Session Continuity	Maintain ongoing IP sessions while changing from the home PLMN to the visiting PLMN	No	TCP/UDP sessions are required to be re-negotiated	-
5G SA compatible UE	UE supporting 5G SA	Often. 5G SA and specific bands are on the roadmap of vendors but this support is not always solid or even implemented.	Time consumed in testing several options.	Testing different vendors. Use of smartphones (last resource).

6.5.2 Legal and regulatory lessons learnt

Table 42: DE TS legal and regulatory lessons learnt

Challenge	Description	Satisfied	Impact	Workaround
Temporal permissions for Experimental networks	Temporal operation of experimental networks in idle bands	No. Tight regulations, complicated and long procedures with public institutions requiring detailed prototype equipment working in a specific band that is agreed after an initial study. The permission ends after some months and it is dependent on arranged or unexpected commercial auctions.	It is difficult to invest in an experimental setup with a lot of conditions to ensure availability	Utilization of commercial networks for outdoor tests.

6.5.3 Reliability and availability lessons learnt

In Table 43, the main lessons learnt are briefly described together with the workaround used in each case, if applicable.

Table 43: DE TS reliability and availability lessons learnt

Challenge	Description	Satisfied	Impact	Workaround
Minimum DL BW not always available	Average DownLink Bandwidth at RX > 20Mbps	Sometimes (day, time, position)	Visual Artifacts or Server Disconnection	No, to ensure scalability
Minimum UL BW not always available	Average UpLink Bandwidth at TX > 20Mbps	Sometimes (day, time, position)	Visual Artifacts or Server Disconnection	QoS Adaptation
Max. Packet Loss for functional US	Packet loss under 2%	Sometimes (day, time, position)	Connection Failure	Restart trial
MEC latency	Average latency similar to Wired < 20ms	Never (it is around 50ms)	Big latencies	Jitter Buffer
5G UE prototypes	Parts endure and are suitable for mobility and testing	Sometimes (SIM dock, cables, Antennas)	After mounting basic tests to check regular functionality	Mobile phones with USB tethering and UE prototypes
5G/LTE mode stability in commercial networks	The network tries to avoid ping-pong between 5G/LTE modes (>10s)	Sometimes (position)	UE is changing from 5G to LTE while it moves. Service interruption.	Not available, depends on commercial network
Steady handover and roaming control in commercial networks	The network tries to avoid ping-pong between cells and PLMNs.	Sometimes (areas)	Handover (performance degradation) or roaming (service interruption.).	Not available, depends on commercial network

7. FI TS DEVELOPMENT, INTEGRATION & ROLL-OUT

7.1 Site Overview

The FI-TS is located within the Otaniemi area of Aalto University (AALTO) campus, in Espoo, Finland. The location is selected with target of having a multi-PLMN environment enabled with a combination of research and commercial 5G networks that provide complementary or overlapping coverage over the Otaniemi roads utilised for the 5G-MOBIX Finland site trials. These roads provide around 1-2 km of test route (see with the target to conduct the local CAM trials in open roads (without seeking road closure permits), with mixed traffic and related complex (realistic) road scenarios (see Figure 72)). This includes scenarios, such as, pedestrian crossings, entering or exiting roundabouts, road intersections and overtake manoeuvres past obstacles. As the test route is located within a signposted built-up area, the speed limit for the trials were 40 km/h.

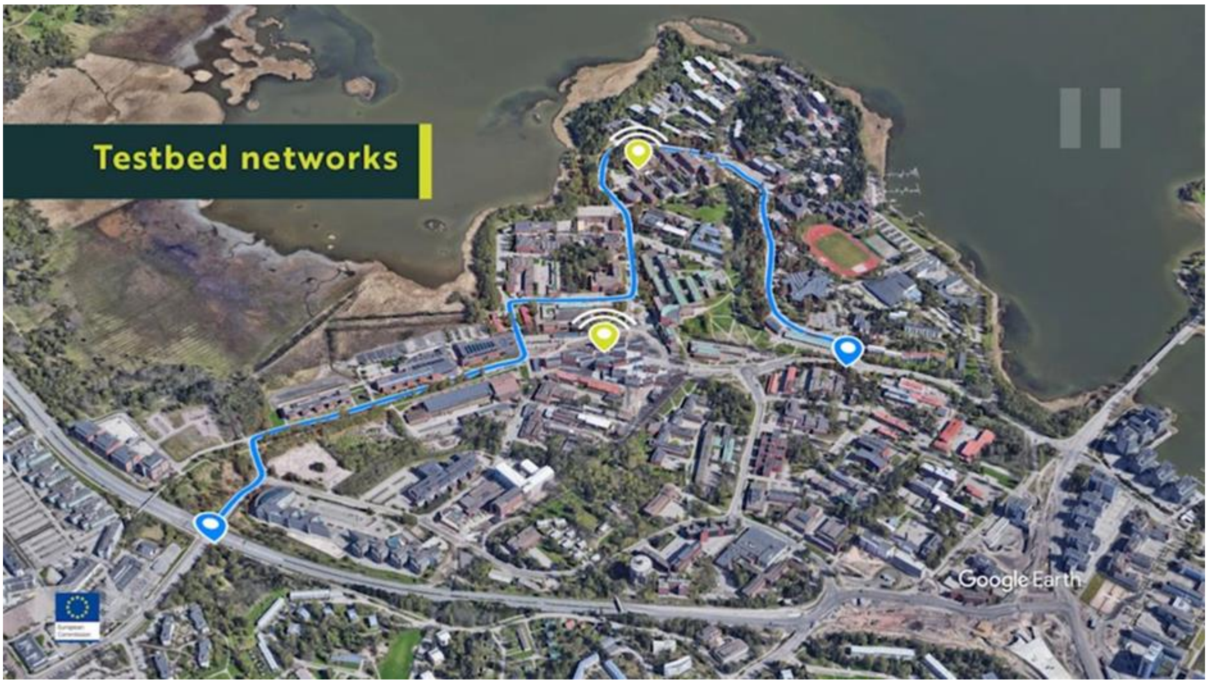


Figure 72: FI-TS test site in the Otaniemi campus

The Finland trial site leverages 4G/5G research testbeds deployed in the Otaniemi area that are continuously being enhanced/upgraded for use in 5G-MOBIX and other local and international research projects. Multiple PLMN instances can be in the test site by virtue of AALTO having access to multiple PLMN-IDs from the local telecom regulator and usage of multiple virtualised 4G/5G core network deployments. Additionally, the FI TS also leverages multiple commercial 5G networks with coverage in the Otaniemi area for additional trialling activities and benchmarking purposes.

7.2 FI Deployed Components

7.2.1 Overview of the deployed components

Table 44: FI Overview of Deployed Components

5G Networks											
	Operator & vendor	*NSA/SA*	Num. gNBs	Freq. Bands	BW	TDD Frames	Network Sync	Backhaul	Core attributes	Core interconnect	Key HO / roaming param.
AALTO PLMN1	AALTO	SA	1	NR: n78	NR: 60 MHz	DDDSU [S = 10D, 2G and 2U]	PTP	Fiber	CRAN, Fronthaul (CPRI Rate-7)	AALTO-AALTO	
AALTO PLMN2	AALTO	SA	1	NR: n78	NR: 60 MHz	DDDSU [S = 10D, 2G and 2U]	PTP	Fiber	CRAN, Fronthaul (CPRI Rate-7)	AALTO-AALTO	
5G Features / Technologies / Configurations addressed											
SA-SA roaming with local breakout architecture, MEC/Edge based operation, multi-SIM											

Vehicles & On-Board Units															
Ve		**Type**	**Make & model**	**SAE Level**	**Vehicle Sensors**	**Vehicle capabilities / functions**	**OB**		**Developer / Vendor**	**Num. OBUs**	**Num. SIMs**	**OS**	**Sup. Mode**	**5G Chipset / Modem**	**OBU sensors**

hicles	**Vehicle 1**	Test vehicle	Renault Twizy	L4	LIDAR, radar	• Object detection • Path following • HD Cameras and LiDAR • Remote monitoring and control • Road legal in mixed traffic, up to 40km/h.	Us	**OBU 1**	Goodmil l	2	2 per OBU	Linux	V2N	Qualcomm /Sierra	None
	Vehicle 2	Passenger car	Ford Focus	Lo	radar	• Machine vision grade camera installation for forward view • RTK capable GPS • ADAS research platform		**OBU 2**	Goodmil l	2	2 per OBU	Linux	V2N	Qualcomm /Sierra	None

Roadside & Other Infrastructure

MEC / Edge nodes	Num. Cloud instances	Num. RSUs	Num. ITS centers	Applications / User Stories	Message type	Supported interface	Supported protocols / APIs	Road side sensors	Supported mechanisms / Features
2 MEC nodes	3	None	0	1. Service discovery EdgeProcessing 2. HD mapping/ EdgeProcessing	Proprietary (ProtoBuf, JSON	Uu	TCP, UDP, WebRTC	None	MEC service discovery and migration
	2	None	1	3. Remote driving app / RedundantNE 4. Video streaming / RedundantNE	Proprietary (ProtoBuf, JSON	Uu	TCP, UDP, RTSP	None	

7.2.2 Measurement Framework

Table 45: FI TS Measurement Tools

Measurement tools used in FI TS		
Tool Name	**Attributes**	**Details**
Keysight Nemo	Description	Commercial drive test tool from Keysight used for conducting agnostic tests (NSA and SA mode) in FI-TS
	PCO Level	Level 0
	PCOs used	UE (5G smartphone and modems), gNB, EPC/5GC, cloud (iPerf server)
	Traffic injection	iPerf3 tool, TCP and UDP traffic, UL and DL directions
DEKRA TACS4	Description (1-3 lines)	Commercial tool from DEKRA used specific testing for different traffic flows in user story ReDr RedundantNE (US4.2)
	PCO Level	Level 1/Level 2
	PCOs used	UE (laptop connected to OBU), ITS cloud, app server, remote operations centre (ROC) used in the user story ReDr RedundantNE (US4.2)
	Traffic injection	iPerf2/iPerf3 tool, TCP and UDP traffic, UL and DL directions
<Measurement Tool3 name>	Description (1-3 lines)	This is a commercial/open-source tool used in the agnostic testing and/or specific testing for <UCC/US ID>
	PCO Level	PCO Level in which the tool measurements are conducted (Level 0, Level 1, or Level 2)
Time Synchronization approaches used in <CBS/TS> for different entities		
Synchronised entities	Synchronisation method or approach (add rows below as needed)	

Example: Vehicle ⇔ Remote Operation Centre (ROC)	NTP used for synchronization between vehicle AD system and the ROC

7.3 Updates During the Deployment process

The deployments in the FI-TS had some updates from what was initially reported in the deployment-oriented deliverables of WP3 (D3.2 [36], D3.3 [37]and D3.4 [33]) that were initially released in early 2021. Some of the updates have been captured in resubmitted versions of D3.2 and D3.4. The updates and rationale for each are summarised below.

- *5G networks*: In the original deployment plan, FI-TS multi-PLMN testbed had two outdoor base station sites (Väre and Otakaari 5), with each site representing a separate PLMN (PLMN-1 and PLMN-2) as it is associated to a distinct core network and assigned a unique PLMN-ID (254 52 and 254 53). The radio equipment deployed in Finland were initially shipped supporting only 5G NSA mode, but an upgrade was later applied to allow also for support for SA mode. The plan was to implement SA-SA roaming between PLMN-1 and PLMN-2, as well as, to have remote deployment of some of the 5GC functions for PLMN-2 to test local breakout. However, the faults in the radio equipment for Otakaari 5 site and delays in shipment of replacement units meant that PLMN-2 has been inactive. This obliged the FI-TS to make more use of multiple commercial 5G networks (NSA mode) as a contingency. Additionally, indoor SA networks implemented with 5G indoor base stations to create two indoor PLMNs was leveraged as a platform for testing the FI-TS SA-SA LBO roaming implementation.

- *Vehicles*: In the original deployment plan, the only vehicle utilised in the FI-TS was the SAE L4 connected and automated vehicle (nicknamed 'Ava') provided by SENSIBLE4. Subsequently, the plan was modified to focus the use of Ava mainly for the FI TS remote driving (RedundantNE) user story. Therefore, the FI-TS also utilised an L0 connected vehicle provided by AALTO for conducting trials for the extended sensors (EdgeProcessing) user story. This reduced dependency on the SENSIBLE4 L4 vehicle allowed for more flexible scheduling of the tests and trials for the EdgeProcessing user story, without the logistical complications of transporting the L4 vehicle to the trial sites and having trained safety drivers.

- *On-Board Units*: In the case of OBUs, in the original planning the FI-TS was testing and evaluating multiple candidate OBUs, but subsequently, the decision was made to focus FI-TS usage only on the Goodmill multi-SIM OBU. This decision was motivated by the fact than an SA-upgrade from the Goodmill OBU later became available (initially NSA mode only) and the close collaboration with the OBU vendor in terms of updating, configuration and testing of the OBU.

- *CAM applications & Other Infrastructure*: There were no significant updates or deviations for the applications and functionalities developed and integrated for the two FI-TS user stories. This also includes the two MEC deployments used in the service discovery and migration implementation as of the realisation of the EdgeProcessing user story.

7.4 FI Verification Results

The verification process for the FI-TS extended sensors user story has been conducted iteratively beginning from the initial development, integration, and testing of the constituent applications (service discovery and HD maps) in the lab environment and subsequent pre-trials and trials (with final trial scheduled for M42). Table 46 gives an overview of the final verification results at the time of reporting. The unverified items are mostly attributed to the delay in implementing the user story in outdoor networks with SA-SA roaming. This has not been an impediment in conducting extended sensors trials with two NSA networks and multi-SIM OBUs used to do network handover that triggers the MEC service discovery and migration. It is noted that the SA-SA LBO roaming implementation is also available in the FI-TS using indoor test network setup and will be used for conducting agnostic trials of the MEC service discovery and migration feature.

Table 46: Final verification results for the FI TS

User Story	Pass	Fail	Partly	Not tested	Completion %
EdgeProcessing	28	0	4	0	97 %
RedundantNE	27	0	3	0	97 %

Similarly, the verification activities for the FI-TS remote driving user story have occurred iteratively from the development and deployment phase of the constituent CAM applications, as well as 5G network assets and OBUs targeted for use in the FI TS trials. This included the initial integration testing of the remote driving and LEVIS video streaming applications in lab or test facilities within the final quarter of 2020 and subsequent early and full trials culminating with the final trial scheduled for M42. Table 46 provides an overview of the verification results for the FI-TS remote driving user story at the current time of reporting. As was with the case with the extended sensors user story, the unverified items in Table 46 are mostly attributed to the delay in implementing the user story in outdoor networks with SA-SA roaming, with the remote driving trials with NSA multi-PLMN environment and multi-SIM OBUs.

7.5 FI Deployment Challenges & Lessons Learned

The FI-TS provided a useful local testing site due to the access to multiple-PLMNs that allow experimental studies on service continuity when transitioning between PLMNs. These PLMNs have been a combination of AALTO research testbeds deployed in both indoor and outdoor environments, as well as multiple 5G networks commercial mobile network operators with coverage in the Otaniemi. The AALTO research networks also include configurations in standalone (SA) mode, which provides a useful complement to the CBC test networks which only operate in NSA mode.

The deployment activities in FI-TS, as well as deployment of some of FI-TS contributions to CBCs had encountered various challenges which nonetheless provided useful insights and lessons. Some of these challenges are summarised below.

7.5.1 Device availability and limitations:

In the half of the project lifetime, the FI-TS had to contend with the scarcity of 5G chipsets and modules, which resulted in delays in testing and trialling activities. Furthermore, when the devices became available there was a limited device support for SA devices on some of the AALTO SA testbeds. This included regional variations in commercial SA devices. For instance, it was noted that Samsung S20 in US supports SA, while similar device sold in Europe does not work on SA. Additionally, restrictions where also noted on the PLMN-IDs that were supportable by SA devices. An example of this is the Nokia XR20 SA device that only supported known commercial PLMN-IDs and did not work with the 254 xx PLMN-IDs allocated for non-commercial test networks in Finland. As the SA upgrades to commercial 5G networks in Finland where not available during project lifetime, this necessitated the use of 999 xx PLMN-IDs that have globally designated for test networks. The resolution of these in many cases required SA devices to rooted or get new firmware to operate in SA mode and the stability of some of the SA devices that do connect now is in many cases not assured. A key lesson here is that support of 5G OBUs and other vehicular connectivity devices should not be taken for granted in multi-PLMN environments, particularly for the relatively immature SA-mode devices.

7.5.2 SA network testing and configuration:

The 5G networks in general present more complex configurations requirements, this is particularly more pronounced for SA mode networks which have been part of test networks in FI-TS. As the SA networks are still at a nascent phase (in terms of commercial deployments), the available support and experience from the ecosystem is still limited. This limitation has also been evident in the contemporary RAN testing solutions, whereby, significant effort and correspondence with test solutions to enable testing in SA networks.

7.5.3 Regulatory constraints:

The spectrum licenses assigned to AALTO is a key enabler for institutional testbed networks. However, as the licenses are for research purposes, there is more stringent restrictions on geographical coverage and available bandwidth (for CAM use cases). For 5G license, the FI-TS had access to 60 MHz spectrum in n78 3.5 GHz TDD band (rather than usual 100 MHz or more, that is usually allocated to commercial operators in Finland). Another restriction was on the number of allocated PLMN-IDs. The increase in demand for PLMN-IDs for private 5G networks seems to add to scarcity of PLMN-IDs e.g., AALTO was assigned 10 PLMN-IDs when project started, but this was later reduced to two PLMN-IDs, which limits the number of PLMNs that could be activated in the test site. Moreover, the regulations also provided restrictions on TDD frame structure, with need for harmonised and synchronised frame structures to minimise interference. This made it unfeasible to test different UL/DL frame configurations that may provide more capacity in the uplink to alleviate bottlenecks, as the user stories in the FI-TS produced more traffic in the uplink direction from vehicle to servers or control centres. The key takeaways from these restrictions include the need to consider approaches for alternative TDD frame structures (e.g., semi-synchronisation) that would enhance uplink throughput, which is essential for CAM use cases. Furthermore, resource scarcity highlight need for sharing models (e.g. for spectrum sharing) to support 5G V2X connectivity in both general or standalone (dedicated or private) 5G PLMNs.

8. FR TS DEVELOPMENT, INTEGRATION & ROLL-OUT

8.1 Site Overview

The French trial site is located in the western part of the Paris region. The site consists of two closed sites TEQMO and Satory. TEQMO has a variety of road configurations including 2.2 Km of highways with three lanes with speed limit of 130 Km/h. For the telecommunication side, the circuit is being equipped with two 5G cmWave networks operated by Orange and Bouygues Telecom operators. Moreover, the site is equipped with C-V2X RSUs, located at each 200m of the highway circuit (as shown in Figure 73).

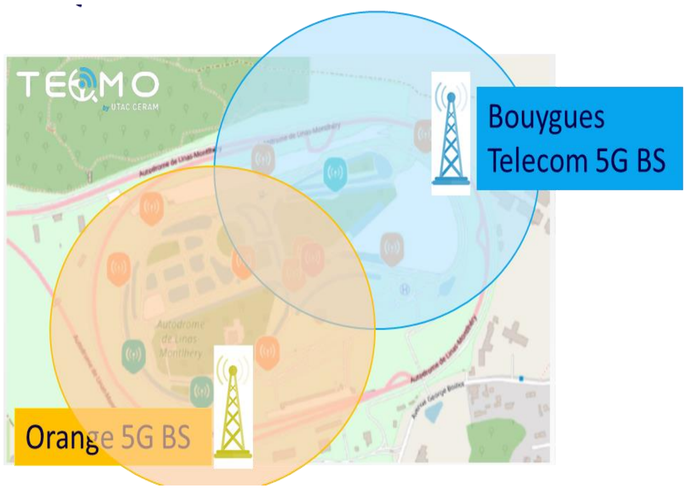


Figure 73: 5G network deployment at the Paris-TEQMO small-scale testbed

Satory has different tracks, including the ROAD track, which is a closed circuit of 3.7 km whose characterises are between those of national road and a departmental road. It allows speeds of around 90 km/h and offers curves with different radii of curvature. At Satory site, FR TS has two 5G networks, a commercial cmWave 5G network operated by Bouygues and an experimental mmWave network operated by TDF. 3 HD cameras, 2 lidars, and 2 MEC are installed at the Satory site. Besides exploiting the above mentioned two closed sites, the FR TS conducted test runs on the open roads in Versailles areas, where different French operators have deployed 5G networks. Open road tests are particularly useful to collect a large amount of data for the solutions of Predictive QoS. (as shown in Figure 74 and Figure 75).

The FR TS is testing the "Infrastructure assisted advanced driving" use case, which deals with a safe lane change manoeuvre dictated from an automated supervision system (of a mobility service provider) in presence of a multi-lane highway with separation signs between the different lanes. Within this user story, the supervision system, which is installed in a predefined MEC (close and/or far MEC), will receive information from connected vehicles (CAMes, CPM, and sensor, particularly camera data) and fuse the data to build an extended perception. Moreover, the supervision system has information about the road layout. After analysing all the input data together with the vehicle related information (location, speed), the MEC will assist CAV in the lane change decision and calculation of the trajectory, guiding the vehicle while it safely changes the lane.

Figure 74: Paris small-scale testbed in Satory

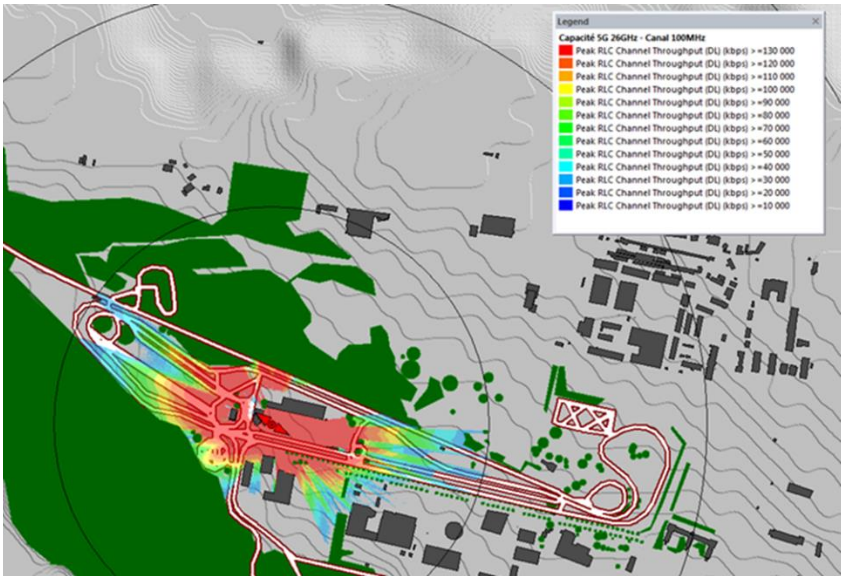


Figure 75: mmWave radio coverage at the Paris-Satory site

As shown in Figure 76, the Integration of SatComm (non 3GPP access, 3GPP Rel 16 [38] and Rel 17 [39]) is used in our test. The focus is to resolve CBC coverage gap and to ensure reliability, resilience and continuity of service. The 5G OBU and the satellite station are both physically connected to the smart router (Pepwave), and connected to the Internet. The smart router uses the principle of link aggregation to ensure continuity of service. That is, both satellite and 5G connection are both active and used at the same time, but with higher priority for 5G connection. The smart router creates a VPN to the other router placed on the server side. This VPN is used to ensure direct communication between the vehicle and the MEC server to exchange MCM (Maneuver Coordination Message) messages. If the cellular coverage is lost, the VPN is still maintained via the satellite connection. This solution is not optimal for exchanging messages between a connected vehicle and a server, but it is essential for ensuring the continuity of service for autonomous or automated driving applications.

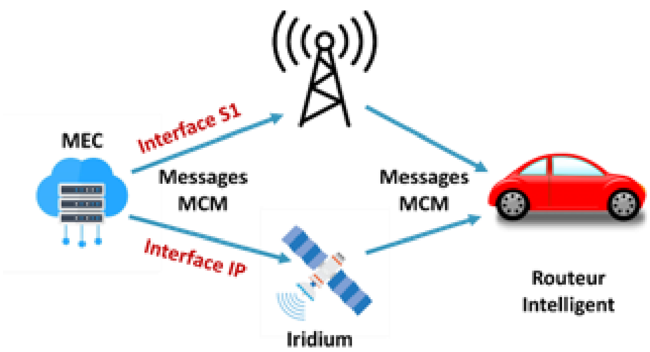


Figure 76: Satelite connectivity architecture

As illustrated in the Figure 77, the architecture is composed of the following:

Vehicle side:

- a smart router (Pepwave MAX HD2)
- a 5G OBU (Gateworks + SIMCOM8300-M2 module)
- a satellite station (Thales MissionLINK 700 Iridium satellite)
- a satellite antenna (Thales MissionLINK 700 Iridium satellite)

Server side:

- a smart router (Pepwave MAX HD2)
- a MEC server

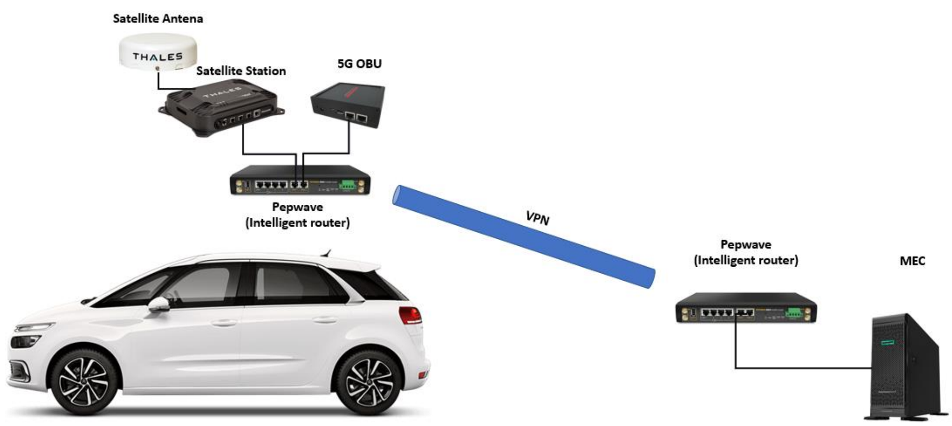


Figure 77: Satellite connectivity scenario

8.2 FR Deployed Components

8.2.1 Overview of the deployed components

Table 47: Overview of FR TS Deployed Components

5G Networks											
	Operator & vendor	***NSA/ SA***	**Num. gNBs**	**Freq. Bands**	**BW**	**TDD Frames**	**Network Sync**	**Backhaul**	**Core attributes**	**Core interconnect**	**Key HO / roaming param.**
	FR PLMN1	NSA	1	700MHz (LTE), 800 MHz (LTE), 1800 MHz 5 (LTE), 2100 MHZ (LTE), 2600 MHz (LTE), 3700-3800 MHz (NR)	20Mhz(LTE) 70MHz (NR)	None	NTP	Fiber	CRAN vs DRAN	N.A	NTP
	FR PLMN2	NSA	1	700 MHz (LTE) 3.5 (NR)	2x30Mhz (LTE) 90MHz (NR)	None	NTP	Fiber	CRAN vs DRAN	N.A	NTP
5G Features / Technologies / Configurations addressed											
Multi-SIM , link aggregation, link selection, roaming											
Vehicles & On-Board Units											

Vehicles		Type	Make & model	SAE Level	Vehicle Sensors	Vehicle capabilities / functions	OBUs		Developer / Vendor	Num. OBUs	Num. SIMs	OS	Sup. Mode	5G Chipset / Modem	OBU sensors
	Vehicle 1	Test vehicle	Renault Zoe	4	GPS RTK, camera, LiDar, RaDAR	Perception, autonomous driving		**OBU 1**	VEDECOM	1	1	Linux	V2N	QUALCOMM/SIMCOM	None

Roadside & Other Infrastructure

MEC / Edge nodes	Num. Cloud instances	Num. RSUs	Num. ITS centers	Applications / User Stories	Message type	Supported interface	Supported protocols / APIs	Road side sensors	Supported mechanisms / Features
MEC 1	1	None	-	Infrastructure assisted Advanced driving	CAMes, DENM, CPM, MCM, MAP	Uu	MQTT,	Cameras, Lidars	V2X/Edge interconnection, local breakout
MEC 2	1	None	-	Infrastructure assisted Advaned driving	CAMes, DENM, CPM, MCM, MAP	Uu	MQTT,	Cameras	V2X/Edge interconnection, local breakout

8.2.2 Measurement Framework

Table 48 gives an overview of measurement tools used in FR TS.

Table 48: FR TS Measurement Tools

Measurement tools used in FR TS		
Tool Name	**Attributes**	**Details**
VEDECOM/TDF measurement tool	Description (1-3 lines)	A tool developed by VEDECOM that captures all the incoming and outgoing application/facilities layer messages (CAMes, CPM, …), calculates per-application KPIs (PDR, throughput, delay) per application for UC-Specific tests. A tool provided by SIMCOM and TDF to measure communication quality at Level 0, used for both the agnostic and UC-specific tests.
	PCO Level	Level 0, Level 1, or Level 2
	PCOs used	OBU, MEC, gNdb, EPC/5GC, cloud used by the tool in the specific UCC tests conducted in the FR TS TS
	Traffic injection	iPerf2/iPerf3 tool, TCP and UDP traffic, UL and DL directions for agnostic tests.
DEKRA TACS4 performance tool	Description (1-3 lines)	Commercial tool from DEKRA used specific testing for agnostic tests cases
	PCO Level	Level 1/Level 2
	PCOs used	OBU, MEC, ITS cloud, app etc.) used by the tool in the agonistic/specific UCC/US tests conducted in the CBC/TS
	Traffic injection	iPerf2/iPerf3 tool, TCP and UDP traffic, UL and DL directions
G-NetTrack Pro	Description	A commercial tool for 5G mobile phones to monitor and log access layer KPIs/
	PCO Level	Level 0
	PCOs used	5G enabled smartphones

	Traffic injection	UDP/TCP data upload/download, PING
Time Synchronization approaches used in <CBS/TS> for different entities		
Synchronised entities	Synchronisation method or approach (add rows below as needed)	
Example: Vehicle ⍰ Remote Operation Center (ROC)	NTP used for synchronization between vehicle AD system and the ROC	

8.3 Updates During the Deployment process

With TDF and Nokia, VEDECOM has deployed a mmWave network at the Satory site, as illustrated in Figure 78.

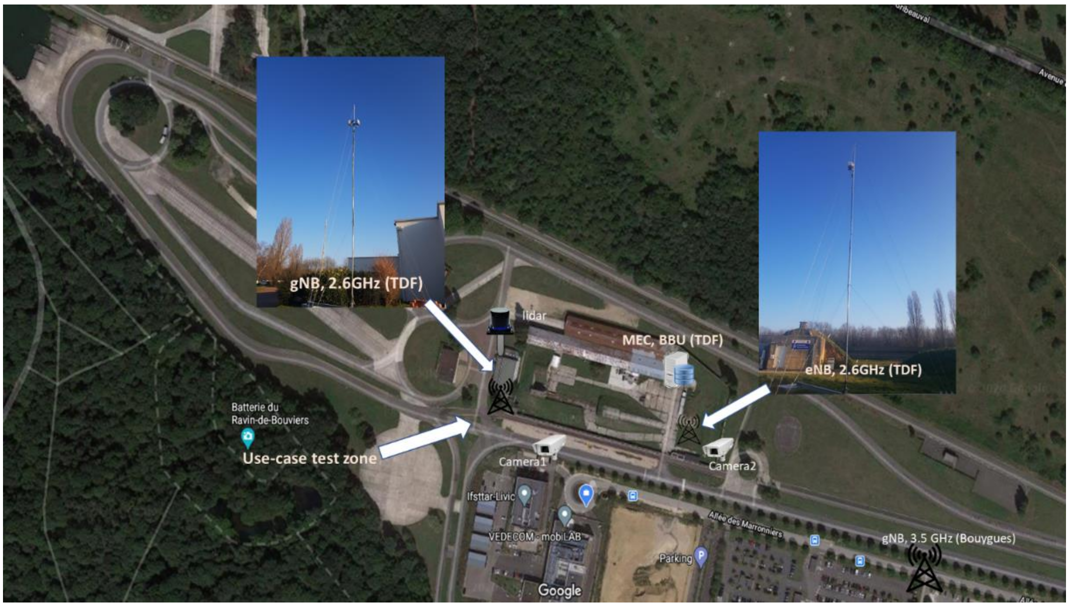


Figure 78: A 5G mmWave network has been deployed at Satory

The network operates at 20 MHz band on the 2.6 GHz spectrum and 200MHz on the 26GHz spectrum. VEDECOM has acquired an authorisation of the utilisation of the spectrum until the end 2022. A MEC has also been deployed in the site, integrating the applications developed by VEDECOM particularly V2X application server, data fusion module, risk analysis, and trajectory guidance module.

OBU upgrade with 5G mmWave

VEDECOM has developed the utilized 5G OBUs in 2020.The OBUs were upgraded with SIMCOM 830 mmWave modem, as shown in Figure 79, so that the OBU can be used under the TDF 5G mmWave network.

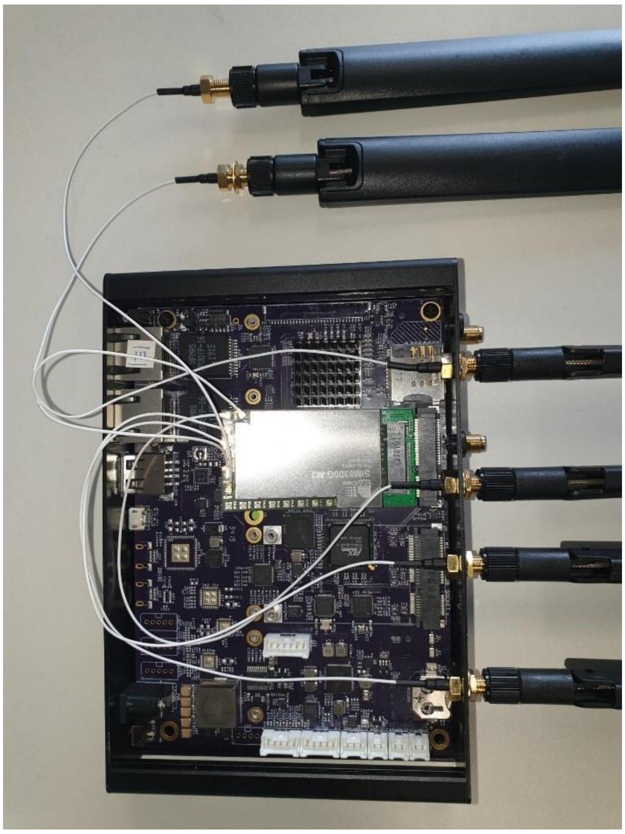


Figure 79: 5G mmWave OBU

8.4 FR Verification Results

The verification process of the FR TS Infrastructure-assisted advanced driving user story has been started in 2020 as soon as developments of individual components and software have started. Table 49 illustrates the final verification status of individual components. As can be seen in the Table 49, the verification processes have been competed except that of OBU related issue and the logging related issue. Indeed, the FR TS successfully deployed a 5G mmWave network and verification of the network has been finalised. In parallel, VEDECOM has developed a 5G mmWave OBU, and its functionality under the mmWave network is not yet completed, resulting in 94% of verification process for the OBU related issues. The execution of the use case trialling under the mmWave network has not yet been done, consequently, the verification process of the logging related issue is completed (92% of completion).

Table 49: Final verifications results of the infrastructure-assisted advanced driving user story

Group	Pass	Fail	Partly	Not tested	Completion %
Vehicle related issues	8	0	0	0	100 %
OBU related issues	8	0	1	0	94 %
Infrastructure related issues	4	0	0	0	100 %
External servers	5	0	0	0	100 %
UE related issues	25	0	1	0	98 %
5G network related issues	7	0	0	0	100 %
Network handover related issues	2	0	0	0	100 %
Network related issues	9	0	0	0	100 %
Subtotal: functional issues	34	0	1	0	99 %
Privacy and security issues	2	0	0	0	100 %
Logging related issues	5	0	1	0	92 %
Total	41	0	2	0	98 %

8.5 FR Deployment Challenges & Lessons Learned

The technical contributions of FR TS include multi-SIM connectivity with and without link aggregation functionalities, predictive QoS, mmWave 5G, satellite connectivity in coverage gap areas, and so on. The majority of the contributions necessitate not only deployment and developments of networks and OBUs, but also development of functionalities that are not-yet fully standardised. During the development, verification, and testing activities, FR TS has faced various challenges that are listed below.

8.5.1 Challenges in acquiring 5G chipsets/modems and developing OBUs:

Since the beginning of the project, some challenges were identified during the field trial from deployment perspectives:

- The FR TS had difficulties to acquire 5G chipsets/modems not only because the technology was new but also as a consequence of the COVID-19 pandemic. While this difficulty has been experienced by almost all the trial sites,
- The FR TS had further challenges in acquiring mmWave devices, which are much more recent and rarer than those operating on sub-6GHz band.
- Furthermore, even after modems are acquired, the FR TS had further difficulties in developing OBUs using the device, more specifically, in having the modems functional under the 5G networks. The difficulty is experienced particularly because the device makers are also at their early stage of producing such devices.

- The FR TS had to do debugging of the modems together with the device maker. The lessons we learnt from this experience is that it is extremely important to work closely with the device makers, in order to have functional systems and to help device makers to improve their products.

8.5.2 Ensuring robustness of equipment (OBU / Sensors / Applications):

To conducts trials for multiple weeks, and months, it is necessary that equipment are robust regardless of the temperature, weather condition, and so on. Ensuring robustness of a system is challenging particularly for equipment, software newly deployed/developed for the project. To ensure robustness various validation tests need to be carried out and the installation/set-up procedure must be clear enough so that any member can correctly install the system.

8.5.3 Harmonizing the solutions when using e.g., different vehicles:

Sometimes it is necessary to integrate equipment/software in different types of systems (e.g., vehicles) that have different interfaces. It is important to carefully specify integration procedure, so that integration of the materials in different systems are harmonised as much as possible (i.e., reducing, as much as possible, the system-dependent modules).

8.5.4 Handling false alarms with the sensors, for instance in windy conditions:

The sensors may issue false alarms due to e.g., strong wind. It is necessary to implement solutions (filter) that reduce such false alarms. Careful sensor setup and calibration are extremely important to avoid and filter false alarms.

8.5.5 Data logging and analysis obtained at various sources:

The 5G-MOBIX common data formats have been defined at a rather later stage of the project, although the developments of components and software modules have been started much earlier. Once common data formats have been finalised, it became clear that, in order obtain complete logs at different communication layers, multiple data sources should not be used and those sources provide data with various formats that are different from the common data format structure. This created a challenge particularly in developing an automatic data analysis tool because it needs to handle various files with largely different formats and sizes. In future projects, it seems necessary to define common data formats at early stage of the project, so that the component developments can be made in order to create data aligned with (as much as possible) the common data format.

9. NL TS DEVELOPMENT, INTEGRATION & ROLL-OUT

9.1 Site Overview

Slicing

The NL TS deploys a 5G SA 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 different use-cases deployed in the NL TS. The slicing has been integrated in the TNO's 5G SA network that has been described in [37] section 7.5.4 and annex D). The slicing technology used in the network is described in section 2.6.7 [37]. The slice IDs (Single Network Slice Selection Assistance Information (S-NSSAI) = Slice Service Type (SST) + Slice Differentiator (SD)) are communicated from the UE to the network after which the network will map the slice IDs to specific QoS guarantees by using the Network Slice Selection Function (NSSF). A local-breakout slicing setup was deployed during trialling to facilitate a direct connection to the MEC node. Each slice has its own UPF at a specific location. **Error! Reference source not found.** shows such a configuration. Where, i n our case, the 'Edge UPF' was located in Helmond and the 'Internet UPF' in The Hague.

Real world scenarios always include a certain amount of background traffic, especially consumer streaming applications (Netflix, YouTube, etc.) add a considerable amount of load to the network's resources. When deploying CAM applications next to this background traffic it can be difficult to provide any QoS guarantees to a CAM vehicle or application. Mechanisms such as relative/absolute priorities between slices are used to further extend the QoS capabilities of the network. In the NL TS absolute priority is configured to guarantee the availability of capacity a specific slice. Two slices are configured: one slice is used for the background traffic, this is called the "internet slice". The other slice is used for the use-cases deployed on the NL TS and is called the "priority slice". The priority slice has an absolute priority over the internet slice, which means that there should always be a configurable (depending on the use-case which is running) amount of radio resources available to the priority slice.

Figure 80 shows how the NL TS added the absolute priority mechanism to the trials. Here, the example of Remote Driving (ReDr) is shown where a high bandwidth video stream from the vehicle to a remote station is introduced into the network. To validate the QoS guarantees assigned for the "priority slice", performance tests are done in three steps. Step 1 is the default setup: no background traffic is generated in the network and only one slice, the "internet slice", is used. Therefore, the network has no difficulty in supporting the video stream. Step 2 shows the addition of a second UE: this UE will generate background traffic (in our case by setting up an Iperf stream to load the network) which will result in packet-loss and added latency for the ReDr video stream, causing the ReDr use-case to be unusable. Step 3 introduces the priority slice. The UE in the ReDr vehicle will be placed in the priority slice whereas the UE generating the background traffic will remain in the internet slice. This configuration allows the ReDr use case to be run with the desired QoS guarantees, resulting in no packet-loss.

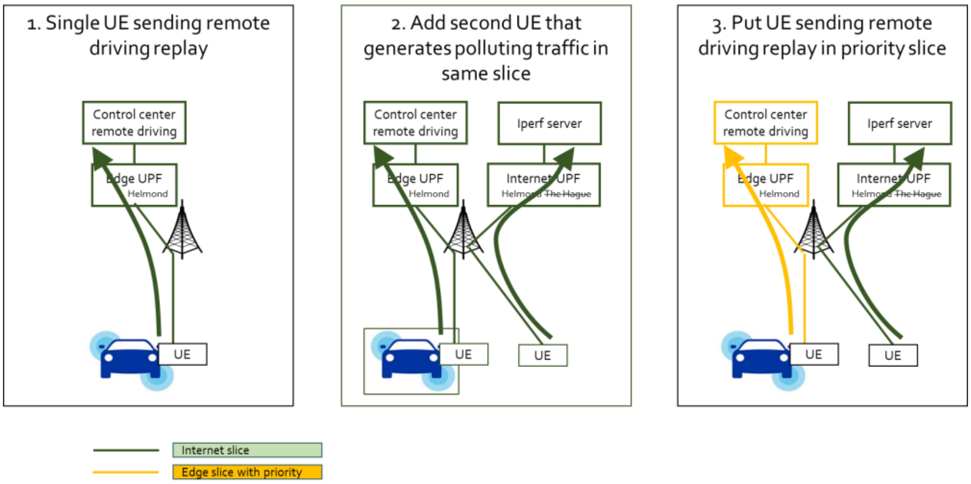


Figure 80: Introducing absolute slicing priority

Roaming

Recent developments include a working 5G SA roaming setup between the TNO and KPN networks for the NL TS. Two (customized Open5GS) cores and two (Ericsson) gNB's are used in Helmond to facilitate roaming. In our case, we implemented LBO roaming. Hence, not all interfaces that are used in our implementation are shown below in Figure 81. Figure 81 shows the NL TS implementation on the roaming functionality.

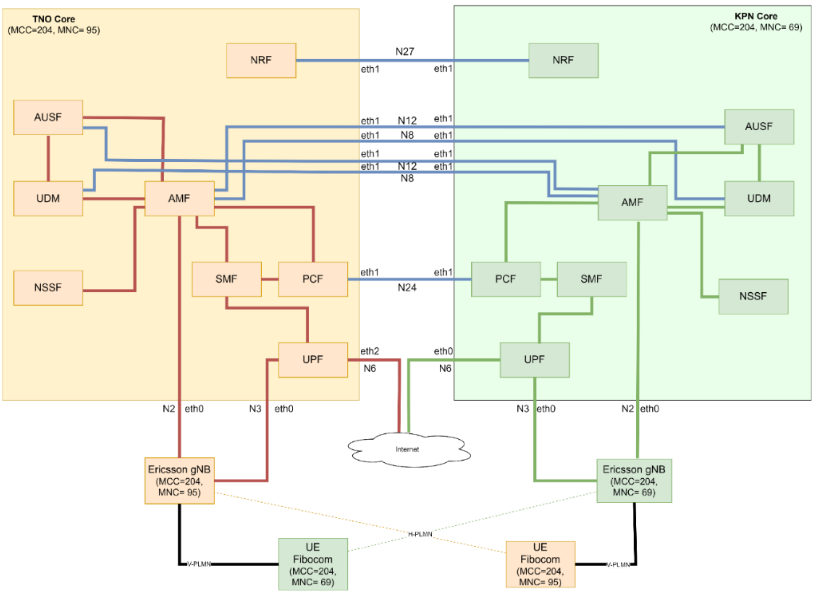


Figure 81: NL TS Roaming Implementation

The 'basic' roaming functionality is in place: the connections between the cores are up and running. The release mechanism from the Release & Redirect functionality, which should be provided by the Ericsson gNB's, was successfully tested. However, the redirect functionality was not. Because the UE does not receive a redirect after the release it causes a ping-pong behavior: the UE releases from the H-PLMN, but because the H-PLMN is still in range when the release is sent, the UE connects back to the H-PLMN. The wanted behavior is obviously that the UE connects to the V-PLMN after the release. This was impossible without the redirect functionality in place.

From the UE's perspective there are some different settings that can be changed to optimize the roaming handover interruption time. During roaming tests, the NL TS experimented with these different settings. The first entry in below list is the least optimized, the last entry is the most optimized:

- (default) the H-PLMN is pre-configured in the SIM.
- (semi-optimized) both the H-PLMN and V-PLMN are pre-configured in the SIM.
- (optimized) both the H-PLMN and V-PLMN are pre-configured in the SIM. The UE is pre-configured to scan in a specific frequency/band when it loses connection.

Results show a significant interruption time decrease when using the semi-optimized or optimized settings. The results for the tests will be reported in deliverable D5.2. Because setting a pre-configured scan frequency in the UE is a tailored solution for this trial site which doesn't scale to real world applications, an MNO will most likely not be able to implement the optimized scenario. However, when the Release & Redirect is implemented and comparing that to the UE-optimized scenario, the optimized scenario should yield comparable interruption times: the 'Redirect' in Release & Redirect should allow for directing a UE into a specific search frequency (e.g., ARFCN).

Slicing and Roaming

The NL TS also supports slicing while roaming. Figure 82 shows the implementation of the roaming functionality highlighting the components that are configured to support the slices: Edge slice with priority, and Internet slice (default priority slice).

The S-NSSAI values (slice IDs) corresponding to both 'Edge slice with priority' and 'Internet' slices, are configured in the gNB for controlling the prioritization of radio resources. In the core, the S-NSSAI values are configured in the AMF for authorizing the slices, in the NSSF for the SMF selection, and in the SMF itself serving the slices.

When the UE roams to the visited PLMN (KPN core), the connection manager of the UE re-connects to the same slice ID as it was previously connected in the home PLMN. The visited PLMN consults the UDM in the home PLMN for the slice IDs authorized based on the UE's subscription. Finally, when the PDU is re-established, the same QoS is achieved in the visited PLMN when compared with the home PLMN, since the radio resources in the gNBs of both networks are configured in the manner.

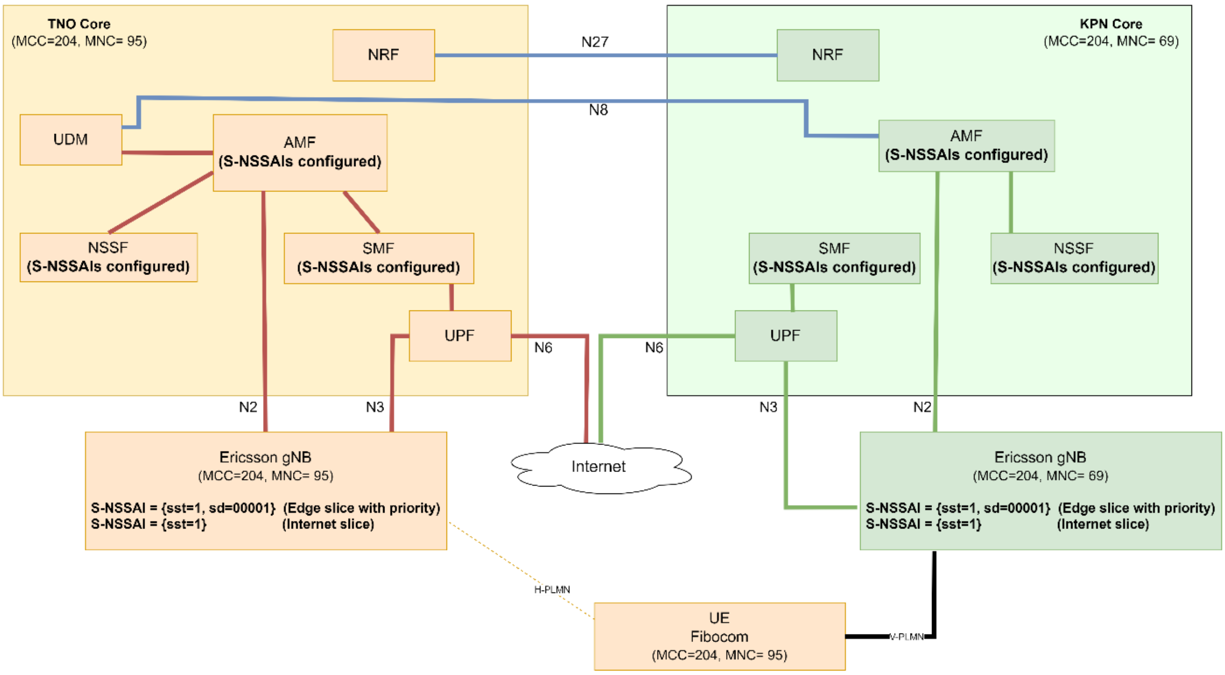


Figure 82: NL TS Roaming with slicing implementation

9.2 NL Deployed Components

9.2.1 Overview of the deployed components

Table 50: NL TS Overview of deployed components

5G Networks											
	Operator & vendor	*NSA/ SA*	Num. gNBs	Freq. Bands	BW	TDD Frames	Network Sync	Backhaul	Core attributes	Core interconnect	Key HO / roaming param.
KPN	KPN	SA	2	3500-3600 MHz	100MHz	TDD2 (DDDSU)	Chrony	Fiber	LBO, MEC, 5G SA	KPN - TNO	5G SA LBO Roaming (Open5GS)
TNO	TNO	SA	1	3650 – 3750 MHz	100MHz	TDD2 (DDDSU)	Chrony	Fiber	LBO, MEC, 5G SA	KPN-TNO	5G SA LBO Roaming (Open5GS)
TU/e	TU/e	(SA)	1	n258	400MHz	simplified	Chrony	Fiber	RAN only	--	--

5G Features / Technologies / Configurations addressed

LBO, LBO roaming, slicing, MEC/Edge based operation

Vehicles & On-Board Units

Vehicles	Owner	Type	Make & model	SAE Level	Vehicle Sensors	Vehicle capabilities / functions	OBUs		Developer / Vendor	Num. OBUs	Num. SIMs	OS	Sup. Mode	5G Chipset / Modem	OBU sensors

	AIIM	Passenger car	Toyota Prius	4	yes	Remote Driving		**OBU 1**	Roboauto / AIIM / TUE	2	1 per OBU	Linux	V2N	WNC	RTK / 4x camera
	Siemens	Passenger car	Toyota Prius	4	yes	Remote Driving		**OBU 2**	Roboauto	1	1	Linux	V2N	WNC	RTK / 4x camera
	VTT	Passenger car	VW Touareg	4	yes	CoCA		**OBU 3**	VTT	2	1 per OBU	Linux	V2N	Netgear	RTK

Roadside & Other Infrastructure

MEC / Edge nodes	Num. Cloud instances	Num. RSUs	Num. ITS centers	Applications / User Stories	Message type	Supported interface	Supported protocols / APIs	Road side sensors	Supported mechanisms / Features
3	-	1 (TNO)	2	1. remote driving 2. collision avoidance 3. extended sensors	CPM, CAMes, MCM, proprietary (remote driving)	Uu	3 MQTT	40 cameras	Edge interconnect, local breakout, slicing.

9.2.2 Measurement Framework

Table 51: NL TS Measurement Tools

Measurement tools used in NL TS		
Tool Name	**Attributes**	**Details**
modem-monitor	Description (1-3 lines)	Proprietary measurement tool to monitor modem (currently support for Fibocom & Quectel) status (state, RSRP, cell id, etc) and network performance (throughput, ping), while recording the lat/lon location on a 1Hz polling basis. Used for agnostic tests
	PCO Level	Level 0, Level 1
	PCOs used	OBU, UE, Edge
	Traffic injection	Ping, Iperf (UL/DL)
MessageLogger	Description (1-3 lines)	Logs all incoming and outgoing ITS messages, as well as application (ExSe) logging. Used for specific tests
	PCO Level	Level 3
	PCOs used	OBU
	Traffic injection	-
MCS Logging	Description (1-3 lines)	Application logging for the CoCA user story is fully integrated in the MCS applications in the OBU and in the MEC applications
	PCO Level	Level 3
	PCOs used	OBU, MEC MCS application
	Traffic injection	-
<Measurement Tool3 name>	Description (1-3 lines)	This is a commercial/open-source tool used in the agnostic testing and/or specific testing for <UCC/US ID>

	PCO Level	PCO Level in which the tool measurements are conducted (Level 0, Level 1, or Level 2)
	PCOs used	PCOs (OBU, gNB, EPC/5GC, MEC, RSU, ITS cloud, app etc.) used by the tool in the agonistic/specific UCC/US tests conducted in the CBC/TS
	Traffic injection	If applicable, what traffic is generated by the tool for agnostic testing?
Time Synchronization approaches used in <CBS/TS> for different entities		
Synchronised entities	OBUs (inc. measurement tools), RSUs, MECs,	
Example: Vehicle - Remote Operation Center (ROC)	Chrony is used for synchronization of the different units.	
Measurements accuracy	Depends on stratum sync level.	
Measurements errors and correction techniques	Additionally, chrony logs are stored to afterwards correct for any clock-drift if necessary	

9.3 Updates During the Deployment process

Recent deployments have been the addition of 5G SA slicing and 5G SA LBO roaming functionality in the NL TS. This has been successfully rolled out in Helmond and is, at the time of writing, being used for use-case and agnostic tests which will contribute to D5.2 [20].

9.4 NL Verification Results

Table 52 gives an overview of the final status of the verification for the different user stories in the NL TS.

Table 52: Final verification results for the NL TS

User Story	Pass	Fail	Partly	Not tested	Completion %
CoCA	34	0	0	0	100 %
CPM	34	1	0	2	92%
5G Positioning	34	0	0	2	94%

For CoCA verification is complete. After the delivery of D3.6 [34], the integration with CTS has been tested.

9.5 NL Deployment Challenges & Lessons Learned

9.5.1 Slicing

The slicing implementation on the UE's accounts can introduce unexpected behaviour when adding multiple slices on the same UE. This is probably because the UE use some internal scheduling for transmitting the packets to the network, for which we don't have direct control. This behaviour is not seen when configuring only one slice per UE. Hence, we chose for the configuration of only configuring one slice per UE in the NL TS.

9.5.2 Network coverage

The CoCA demands a location where automated driving can be performed with vehicles connected to different networks. The KPN and TNO network coverage overlaps at a stretch of the A270 east of the Vaarle resting place. The only location where automated driving can be performed is the parking place of Vaarle, which can be closed from traffic with permission of the Province of North-Brabant. Initial tests performed in Q1/2021 proved coverage, however the receipt of the TNO network during the actual trial in September 2021 was not so good, due to foliage blocking line-of-sight between the OBU antenna and the gNB antenna. Tests performed in April 2022, when there was no foliage, provided much better receipt and lower latency values then for the tests performed in September 2021. It is hence important to verify which factors may affect the tests, such as foliage, and to select the test environment with as much Line of Sight as possible.

9.5.3 Roaming

For roaming, we chose to focus on LBO roaming with Release & Redirect. 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.

For the Release & Redirect functionality we are heavily dependent on the provider of the gNB (Ericsson) for support. Activating this functionality in the gNB requires a very specific configuration. However, until now we (with the support from Ericsson) have not been able to.

On top of that, both the UE and gNB must support the functionality needed for the Release & Redirect mechanism to work. We have seen that this is not trivial: only the recent version of our UE's (Fibocom) firmware supports this functionality. Also, on the gNB side (at the time of writing) it remains an open question if all the required functionalities are implemented in our current firmware version.

To use 5G SA, three 5G SA capable components need to be deployed: the core, the GnB and the UE. For 5G SA roaming no off-the-shelf (both commercially and open-source) core implementation was readily available (in 2021). Hence, we diverted to an open-source implementation (Open5GS) to implement the roaming functionality in-house. For the UE's and GnB's functionality we are dependent on our suppliers, respectively Fibocom and Ericsson. Even though the needed features are already standardized, it's up to the suppliers to implement and provide the features needed. Currently, it seems that the needed features are beyond state-of-the art. Based on this, and our efforts 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.

9.5.4 mm-Wave 5G and Localization

A full 5G SA mm-wave network could not be deployed due to unavailability of components and the limited support for high-resolution angular information supported by commercial equipment. The deployed mm-wave with simplified protocol stack nonetheless yields some interesting insights: first, 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 resulting overall throughput decrease, pointing to a need for improved beam acquisition strategies and required support for adaptive beamforming at both UE and gNB side if analogue beamforming is employed. Second, with regards to localization, the observed channel behaviour in a built up environment with modern concrete-steel facade buildings suggests the mm-wave channel to be sparser than expected, making it easier to identify main signal components and relevant reflection points, while at the same time reducing the amount of available information; as a result, further improvements to the localization algorithms are likely to be needed to achieve the targeted localization performance.

10. CN TS DEVELOPMENT, INTEGRATION & ROLL-OUT

10.1 Site Overview

CN trial site is mainly located in the enclosed section of the eastern area of Shandong Academy of Sciences and the section of Shandong Binlai Expressway, and contains an Intelligent Networked Highway Test Base, covering both urban roads and highways as shown in Figure 83. It is mainly focused on remote data ownership. Three test cases for driving, cloud-assisted advanced driving and cloud-assisted vehicle formation were verified. The RSU and OBU equipment used by CN TS meets EU and Chinese standards respectively, and all test sites cover at least the network services of two different operators.

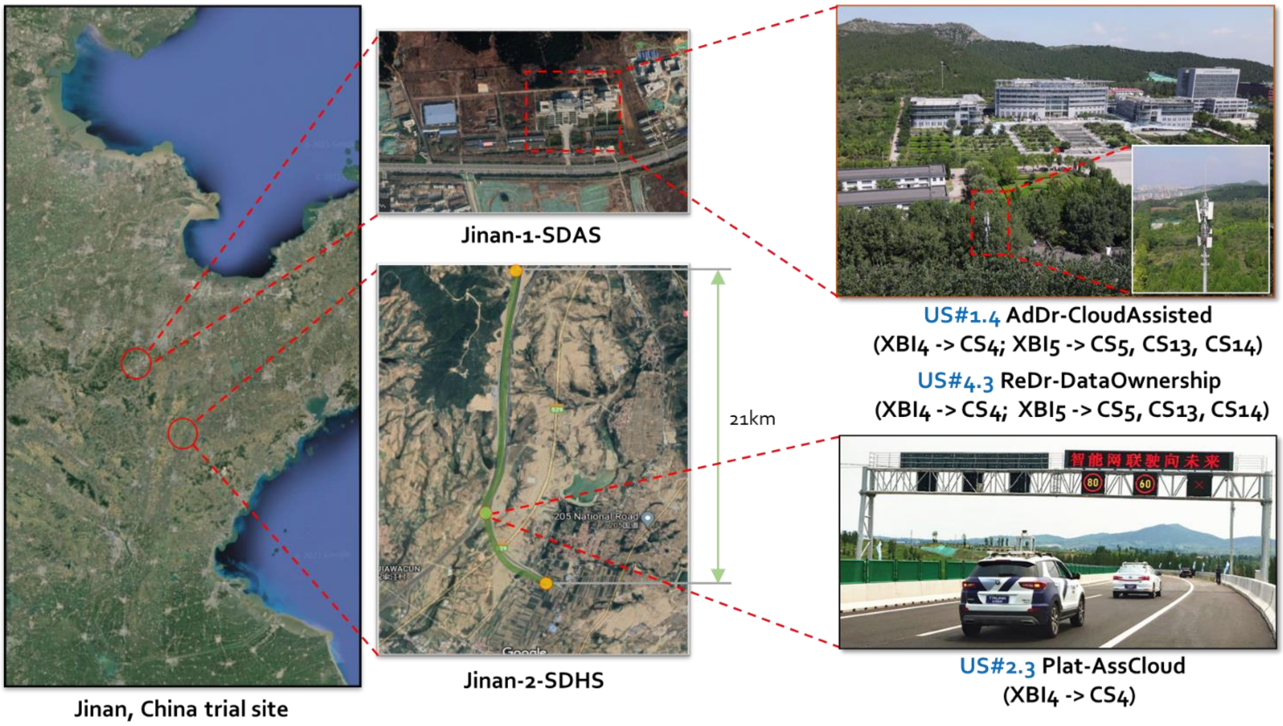


Figure 83: Overview of the CN trial site

10.2 CN Deployed Components

10.2.1 Overview of the deployed components

Table 53: CN TS Overview of deployed components

5G Networks											
	Operator & vendor	*NSA/SA*	Num. gNBs	Freq. Bands	BW	TDD Frames	Network Sync	Backhaul	Core attributes	Core interconnect	Key HO / roaming param.
CN PLMN 1	CMCC(ZTE)	NSA	3	n41 n78 n79	2515MHz-2675MHz 4800MHz - 4900MHz	N/A	GPS/BDS	Fibre	NFV/SDN, etc.	Direct-fibre interconnection	N/A
CN PLMN 1	CMCC(HUAWEI)	NSA	3	n78	3500MHz-3600MHz	N/A	GPS/BDS	Fibre	NFV/SDN, etc.	Direct-fibre interconnection	N/A
5G Features / Technologies / Configurations addressed											
(e.g., Home-Routing, Local Break-out, S1 base HO, S10 based HO, Direct line, SA slicing, Uu / PC5 communication, MEC/Edge based operation, Cloud based operation, multi-SIM, mmW etc.)											

Vehicles & On-Board Units															
Veh		Type	Make & model	SAE Level	Vehicle Sensors	Vehicle capabilities / functions	OBUs		Developer / Vendor	Num. OBUs	Num. SIMs	OS	Sup. Mode	5G Chipset / Modem	OBU sensors

icles	**Vehicle 1**	car	Self-driving vehicles transfor med from existing vehicles	L4	Lidar, camera, millimeter wave radar, OBU	As the main vehicle for various tests of remote driving and advanced driving		**OBU 1**	SDAS	1	1	ubunt u	V2N, V2V, etc.	MH5000	gnss,adas, dms
	Vehicle 2	Experim ental car	Wire control chassis + replacea ble shell assembly	L3	Lidar, camera, OBU	As a background vehicle for advanced driving test, and V2V communication test with the main vehicle		**OBU 2**	SDAS	1	1	ubunt u	V2I, V2V, V2N	MH5000	gnss,adas, dms
	Vehicle 3	Truck	Sinotruk's existing vehicles	L2	Camera, millimeter wave radar, OBU	Carry out vehicles platoon communication test		**OBU 3**	SDAS	1	1	ubunt u	V2I, V2V, V2N	MH5000	gnss,adas, dms

Roadside & Other Infrastructure

MEC / Edge nodes	Num. Cloud instances	Num. RSUs	Num. ITS centers	Applications / User Stories	Message type	Supported interface	Supported protocols / APIs	Road side sensors	Supported mechanisms / Features
1	1xAliyun Cloud	3		1. Plat-AssCloud 2. AdDr-AssCloud 3. Remote Driving	CAMes, DENM, etc	Uu, PC5	MQTT, SFTP, etc.	UHD camera, Traffic light	e.g., geolocation, HO detection, app state transfer across MECs, etc.

10.2.2 Measurement Framework

Table 54: CN TS Measurement Tools

Measurement tools used in CN TS		
Tool Name	**Attributes**	**Details**
TCPDump	Description (1-3 lines)	Open-source tool to capture data-network in the specific tests for Advanced Driving (US1.4), Platooning (US2.3) and Remote Driving (US4.3).
	PCO Level	Level 1
	PCOs used	OBUs and RSUs provided by SDIA
	Traffic injection	N/A
DEKRA TACS4	Description (1-3 lines)	Commercial tool from DEKRA used specific testing for different traffic flows in user story Advanced Driving (US1.4), Platooning (US2.3) and Remote Driving (US4.3)
	PCO Level	Level 1/Level 2
	PCOs used	UE (laptop connected to OBU), ITS cloud, app server, remote operations centre (ROC) used in the user story Advanced Driving (US1.4), Platooning (US2.3) and Remote Driving (US4.3)
	Traffic injection	iPerf2/iPerf3 tool, TCP and UDP traffic, UL and DL directions
<Measurement Tool3 name>	Description (1-3 lines)	This is a commercial/open-source tool used in the agnostic testing and/or specific testing for <UCC/US ID>
	PCO Level	PCO Level in which the tool measurements are conducted (Level 0, Level 1, or Level 2)
	PCOs used	PCOs (OBU, gNB, EPC/5GC, MEC, RSU, ITS cloud, app etc.) used by the tool in the agonistic/specific UCC/US tests conducted in the CBC/TS
	Traffic injection	If applicable, what traffic is generated by the tool for agnostic testing?
Time Synchronization approaches used in <CBS/TS> for different entities		
Synchronised entities	Synchronisation method or approach (add rows below as needed)	

Example: Vehicle Remote Operation Center (ROC)	NTP used for synchronization between vehicle AD system and the ROC
Measurements accuracy	
Measurements errors and correction techniques	

10.3 Updates During the Deployment process

The local test site in Jinan-1-SDAS has deployed 5G Infrastructure with a full 5G SA covered. SDIA built the cloud server, and the DUT made the application on this server. And the Jinan-2-SDHS test site has completed a 2km expressway (Shandong High-Speed Information Group Co., Ltd.) in the northern part of Miaoshan, with three full-width gantry and Hawkeye cameras with a spacing of 500 meters. In addition, 5G, LTE-V, DSRC networks and other heterogeneous networks are also installed on mechanical and electrical equipment such as roadside lidars and V2X roadside devices for 3D high-precision maps and other vehicle-road collaborative applications. We have developed and tested the data transmission application for servers, edge, and vehicles. And we are still optimizing and logging the application to meet the lower latency indexes.

The test site has completed a 2km expressway (Shandong High Speed Information Group Co., Ltd.) in the northern part of Miaoshan, with three full-width gantry and Hawkeye cameras with a spacing of 500 meters. In addition, 5G, LTE-V, Dedicated Short Range Communication(DSRC), Enhanced Ultra High Throughput (EUHT), Wi-Fi networks and other heterogeneous networks are also installed on mechanical and electrical equipment such as roadside lidars and V2X roadside devices for 3D high-precision maps and other vehicle-road collaborative applications.

10.4 CN Verification Results

Table 55: Final verification results for the CN TS

User Story	Pass	Fail	Partly	Not tested	Completion %
CloudAssisted	38	0	2	3	95 %
AssCloud	33	0	2	1	94 %
DataOwnership	31	0	2	1	93 %

The verification activities for the CN-TS Cloud assisted user story (US#1.4) have been iteratively rolling from the initial development, integration, and testing of the constituent applications. Table 55 gives an overview of the final verification results at the time of reporting. Our results showed the OBU with a multi-band 5G

NR/LTE-FDD/LTE-TDD/HSPA+ module solution that supports R15 5G NSA/SA data transmission to 4.0 Gbps. These results measured the performances of TCP/UDP data flows in our test. The results also showed that a full 5G SA covered in SDIA enhanced the QoS of transmission from the vehicle to the cloud server. Moreover, the logging capabilities of the OBUs, RSU and MEC have been in place for three user stories in CN TS. The unverified items are attributed to the logging data of test results is in progress to be shared in the agreed format and uploaded to the CTS Centre.

In the verification for the Cloud Assisted Platooning (US#2.3), we have designed three use cases (CN-2.1, CN-2.2, CN-2.3) to deal with XBI_4 solved by CS-4. V2X road safety services are applied to cloud-assisted platooning systems through RSUs and OBUs. In the Cloud Assisted Platooning US, two vehicles are provided by CNHTC (the leading vehicle and the following vehicle). In CN TS, the leading vehicle processes the Cooperative Routing Messages (CRMs) received from one cloud server, which provides routing planning for the platoon. The vehicles exchange information to give the correct commands to the follower vehicle. The unverified items are attributed to the logging data of test results is in progress to be shared in the agreed format and uploaded to the CTS Centre.

In the verification for Remote Driving (US#4.4), we have analysed the cross-border issues involved in CN specific user stories to apply proper solutions. The situational awareness in this US from a multitude of data-rich sensors that need to be transferred to the remote location, so we have designed three use cases (CN-3.1, CN-3.2, CN-3.3) to deal with XBI_4 and XBI_5. We have developed and tested the data transmission application for server, edge, and vehicles. Additionally, logging in the on-board computer of vehicle and cloud server for controller message has been tested. The applications in the OBU from DATANG were tested in Shanghai, and the exchange of privacy-related data, including vehicle related information and video, is in line with EU guidelines (GDPR, C-ITS security policy). The unverified items are attributed to the ongoing optimization of the application to get lower latency and the validity of the timestamps in the logs.

10.5 CN Deployment Challenges & Lessons Learned

In CN TS, we need to simulate the problem-solving of 5G cross-border issues in the Jinan. SDIA built the cloud server, and the DLUT made the application on this server. And the Jinan-2-SDHS test site has completed a 2km expressway (Shandong High-Speed Information Group Co., Ltd.) in the northern part of Miaoshan, with three full-width gantry and Hawkeye cameras with a spacing of 500 meters. Two challenges were identified during the field trial from a deployment perspective:

- In our initial test results, the vehicle relied on one R15 5G module solution to support the communication of control plane. When the vehicle crossed the simulated cross-border areas, the OBU was switched to another MNO, the communication was interrupted due to signalling redialing. We cannot guarantee the required service continuity.

- We rely on the public link aggregation mode in the started test, the 5G network performance are affected significantly by the network fluctuation.

In order to tackle the technical challenges above, we deployed the test vehicle with double 5G communication modules to provide redundancy to complete signalling process and minimize session interruption time when moving multiple MNOs coverage areas. We deployed a dedicated 5G shared MEC in the enclosed site to provide more bandwidth for use cases and we learned the following lessons:

- The trigger time of handover procedure must be configured in both OBU and gNB to ensure the coordination between two the communication modules.

- In order to ensure the better service continuity, the handover location needed to be obtained in advance.

According to the dynamic zero-COVID policy of China, we have many cooperation issues on our site. Firstly, the CN team worked in different cities, such as DUT researchers in Dalian city, the SDIA, CNHTC and SDHS researchers in Jinan city and DATANG in Beijing city. Thus, the full verification processes could not be completed as originally planned. In order to promote the project's progress, we tried to make online meetings and forums to solve cooperation issues. Also, we got remote help from our partner at the Aalto University.

11. KR TS DEVELOPMENT, INTEGRATION & ROLL-OUT

11.1 Site Overview

For the test trial of KR Tethering via Vehicle and remote control driving, the following network layout configuration is provided as seen in Figure 84.

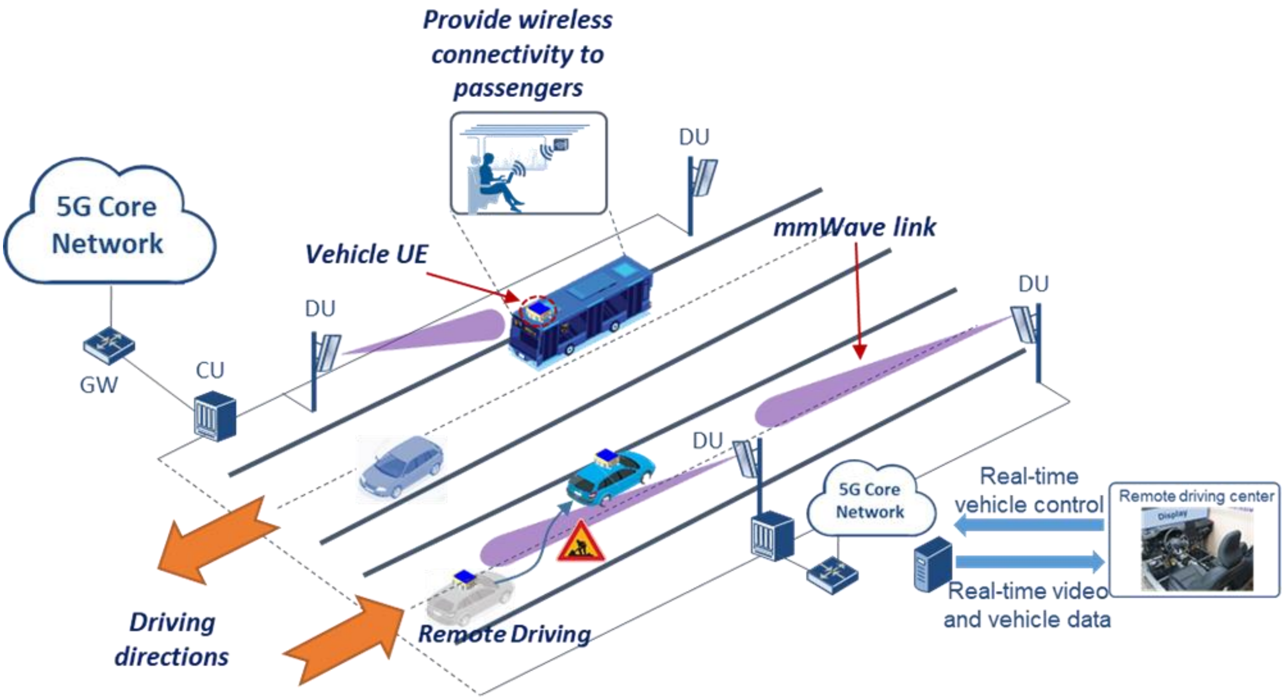


Figure 84: KR network layout for Tethering via Vehicle and Remote Control Driving

The proposed mmWave vehicular communication system is based on the 5G NR. It has the following system aspects:

- gNB functionalities are split into central units (CUs) and distributed units (DUs). The split point is between MAC and PHY. CUs process higher layer protocols and DUs are involved in physical layer and RF processings.
- Optical fibre is used for the fronthaul connectivity between CUs and DUs.
- Each CU is further connected to the 5G core network.
- Vehicle UEs are installed on vehicle driving fast on roads (e.g., highways). Vehicle UEs establish wireless backhaul to the DUs installed along the road, and then provide wireless services to the passengers through in-vehicle relaying.

- mmWave is employed for the wireless backhaul service. The carrier frequency ranges 22-23.6 GHz.
- A UE-side beamforming scheme is employed to form a narrow beam and steer it to the direction of the DU antenna.

More detailed description on the KR Tethering via Vehicle trial setup is illustrated in Figure 85.

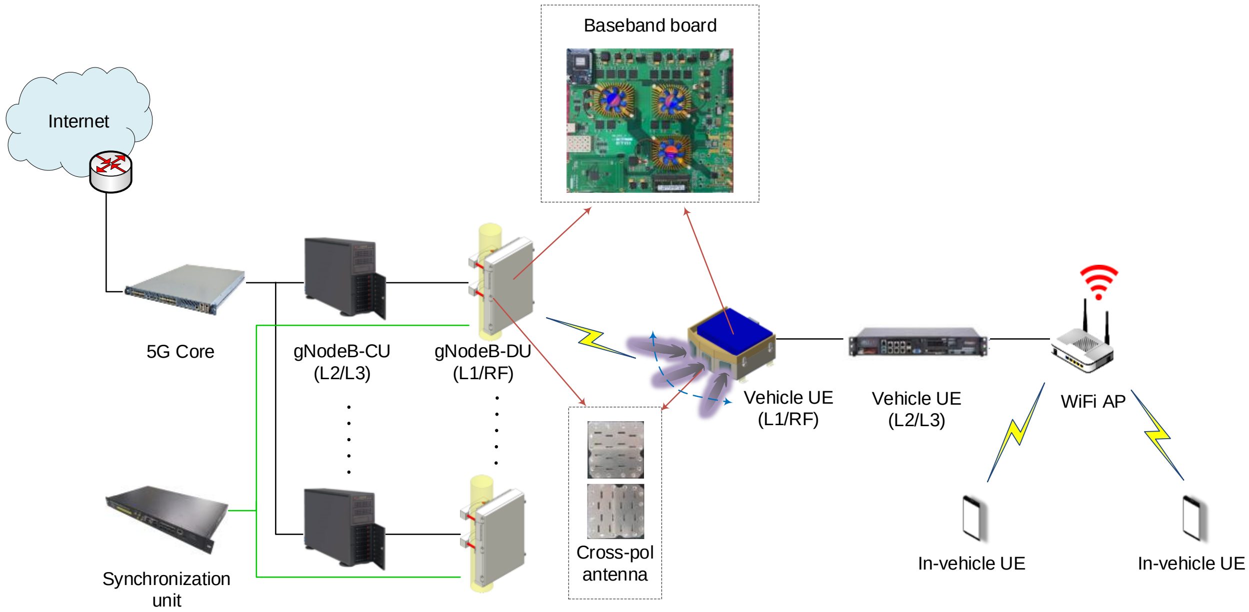


Figure 85: KR trial 5G network setup

In the figure, each node has its own functionality as follows:

- gNB-CU processes L2/L3 functionalities of gB. The CU functionalities are implemented via software.
- gNB-DU implements L1 baseband and RF functionalities. The L1 baseband processing is implemented using field-programmable gate arrays (FPGAs).
- 5G Core manages gNB-CU. The 5G Core is connected to the Internet.
- The RF module can process up to 600 MHz wideband mmWave signal at a center frequency of 22.6 GHz. Two independent RF paths are placed for the transmit and receive paths.
- A slotted array waveguide antenna is employed both at the gNB-DU and Vehicle UE. Two cross-polarization is assumed between the two RF paths.
- 10G Ethernet is employed for the interconnection between the CU and DUs. Optical fiber is used to connect between the CU and DUs. A dense wavelength-division multiplexing (DWDM) scheme is used for the multiplexing of the signals from/to different DUs.

11.2 KR Deployed Components

11.2.1 Overview of the deployed components

Table 56: KR TS Overview of deployed components

5G Networks											
	Operator & vendor	*NSA/SA*	Num. gNBs	Freq. Bands	BW	TDD Frames	Network Sync	Backhaul	Core attributes	Core interconnect	Key HO / roaming param.
KR PLMN 1	ETRI	SA	5	FACS band (22-23.6 GHz)	600 MHz	DL:UL = 7:1	Sync over fiber	Fibre	DRAN		
5G Features / Technologies / Configurations addressed											
(e.g., Home-Routing, Local Break-out, S1 base HO, S10 based HO, Direct line, SA slicing, Uu / PC5 communication, MEC/Edge based operation, Cloud based operation, multi-SIM, mmW etc.)											

Vehicles & On-Board Units															
Vehicl		Type	Make & model	SAE Level	Vehicle Sensors	Vehicle capabilities / functions	OBUs		Developer / Vendor	Num. OBUs	Num. SIMs	OS	Sup. Mode	5G Chipset / Modem	OBU sensors
	Vehicle 1	SUV	Renault Arkana	4	4	N/A		OBU 1	ETRI	1	0	Linux	V2N,	ETRI modem	
	Vehicle 2	Van	Hyundai Solati	0	No	N/A									

e s															

Roadside & Other Infrastructure									
MEC / Edge nodes	**Num. Cloud instances**	**Num. RSUs**	**Num. ITS centers**	**Applications / User Stories**	**Message type**	**Supported interface**	**Supported protocols / APIs**	**Road side sensors**	**Supported mechanisms / Features**
1	s	5	1	1. Remote driving 2. Tethering via vehicle	IP traffic	Uu	HTTP, FTP, etc.	0	Handover, etc.

11.2.2 Measurement Framework

Table 57: KR TS Measurement Tools

Measurement tools used in KR TS		
Tool Name	**Attributes**	**Details**
Physical-layer performance monitoring display	Description	Self-developed monitoring software for evaluating physical-layer performance (e.g., received SNR, transmit data rate, receive data rate) is used both on vehicle OBU and gNB DU.
	PCO Level	Level 0
	PCOs used	OBU and gNB
	Traffic injection	N/A
Benchbee Speed Test	Description	A free mobile application, developed by a Korean company (BENCHBEE Co. LTD), is installed on a smartphone device and used for testing Wi-Fi network quality (download/upload speed and latency) in the Tethering via Vehicle test case (UCC 5/US 2).
	PCO Level	Level 1
	PCOs used	Smartphones carried by onboard passengers
	Traffic injection	N/A
Remote Control Driving Status Monitoring Tool This is a commercial/open-source tool used in the agnostic testing and/or specific testing for <UCC/US ID>	Description	Self-developed RCV status monitoring software for evaluating
	PCO Level	PCO Level in which the tool measurements are conducted (Level 0, Level 1, or Level 2)
	PCOs used	PCOs (OBU, gNB, EPC/5GC, MEC, RSU, ITS cloud, app etc.) used by the tool in the agonistic/specific UCC/US tests conducted in the CBC/TS
Time Synchronization approaches used in <CBS/TS> for different entities		

Synchronised entities	Synchronisation method or approach (add rows below as needed)
Example: Vehicle ⇔ Remote Operation Centre (ROC)	NTP used for synchronization between vehicle AD system and the ROC
Measurements accuracy	
Measurements errors and correction techniques	

11.3 Updates During the Deployment process

The KR TS deployment details have been reported in the former WP3 deliverables D3.2 [36], D3.3 [37] and D3.4 [33]. There have been no substantial changes in the deployed components, beyond what we reported earlier.

11.4 KR Verification Results

As illustrated inFigure 86, KR TS is responsible for two USs, Tethering via Vehicle (US 5.2) and Remote Driving (US 4.5), and a self-developed mmWave 5G NR communication system was used for their demonstrations.

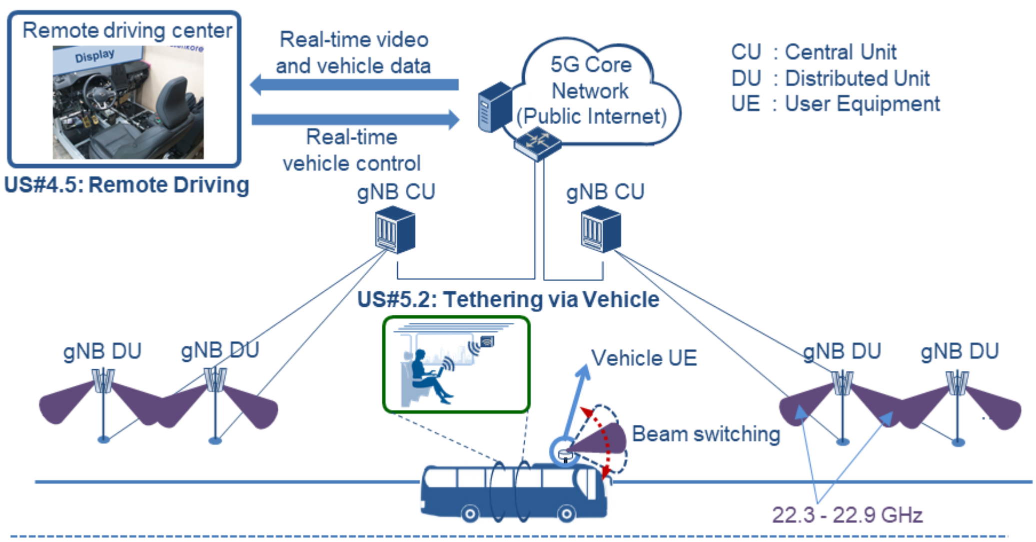


Figure 86: User stories and network architecture of KR TS

Before the demonstration of each US, we first conducted system validation to test the key functionalities and verify whether the system meets the performance requirements of the two USs. The key requirements for the realization of the USs are downlink and uplink data rates and can be summarized as follows:

- Remote driving (US 4.5)
  - **Downlink data rate** required to transmit real-time vehicle control information: **1 Mbps**
  - **Uplink data rate** required to transmit real-time video and vehicle data: **50 – 100 Mbps**
    - A total of 8 driving cameras were installed on the front, rear, and side of the vehicle, and at least 4 cameras were used for the demonstration.
    - According to the 3GPP TR 22.886 [40], the uplink data rate required to deliver two videos with H.265/HEVC HD video codec is 25 Mbps.
- Tethering via vehicle (US 5.2)
  - **Downlink data rate** required for providing broadband onboard Wi-Fi service: **1000 Mbps**
  - **User-experienced data rate of onboard Wi-Fi: 100 Mbps**

To verify the system performance, PHY-to-PHY performance evaluation was first conducted both in indoor and outdoor environments. During the indoor testing, the measured maximum downlink and uplink data rates were 3 Gbps and 200 Mbps, respectively, using six component carriers (CCs). Then, outdoor testing was conducted on ETRI and KATECH's proving ground to evaluate the uplink data rate, as shown in Figure 87 and Figure 88. When three CCs were allocated to the vehicle UE, an uplink data rate over 50 Mbps was measured in most parts of the measurement route, which enables the vehicle UE to transmit four-camera video to the remote driving centre in real-time. Also, when six CCs were assigned to a vehicle UE, more stable data rate performance can be achieved within the entire demonstration route, and videos of up to 8 cameras (100 Mbps) can be delivered in real-time.

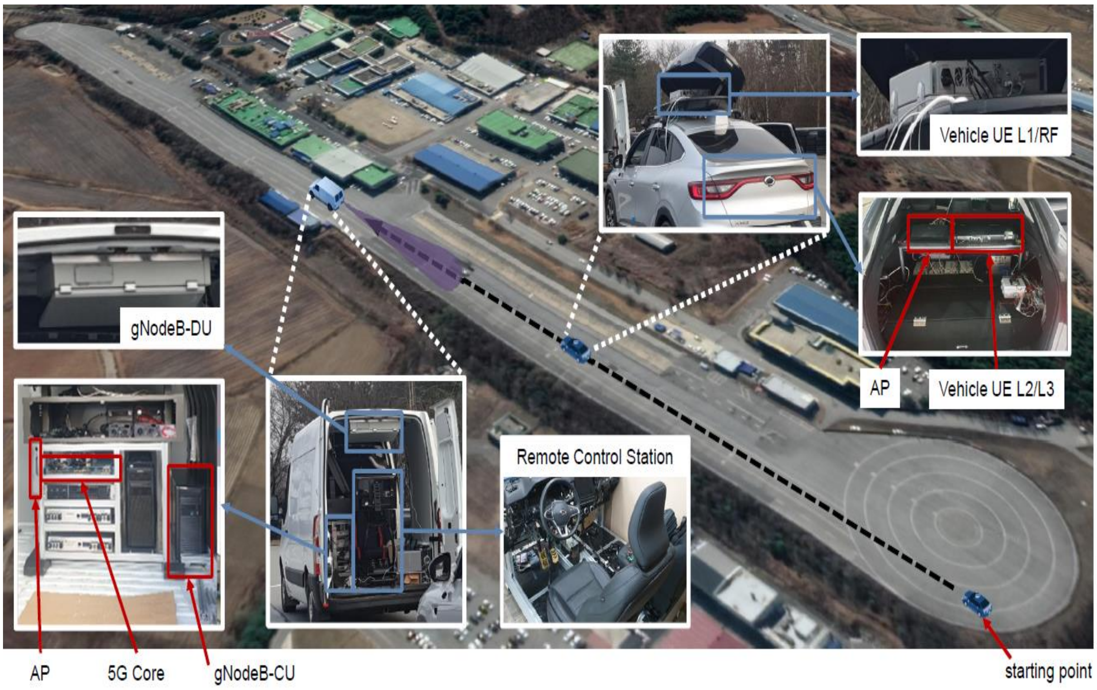


Figure 87: Remote control test setup and testing in KATECH proving ground, South Korea

In addition, as shown inFigure 88, additional outdoor testing was carried out on an urban road in Daejeon city, south Korea, it was observed that the beam switching techniques can contribute to the performance enhancement when the vehicle changes line or travels on a curve and that the maximum downlink data rate of up to 2.5 Gbps can be achieved using the beam switching technique.

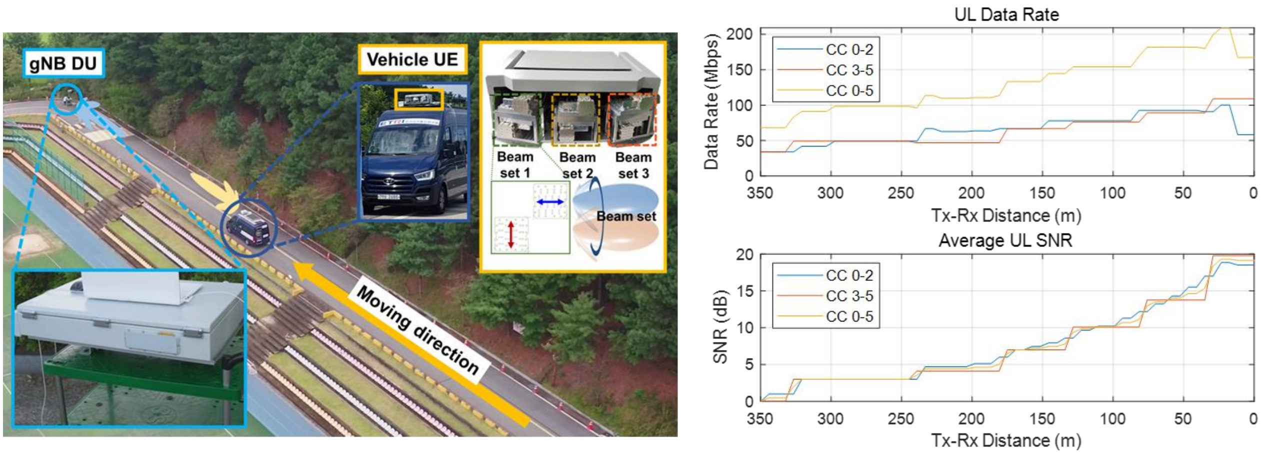


Figure 88: Measured receive SNR and uplink data rate of PHY-to-PHY testing in ETRI premises, south Korea

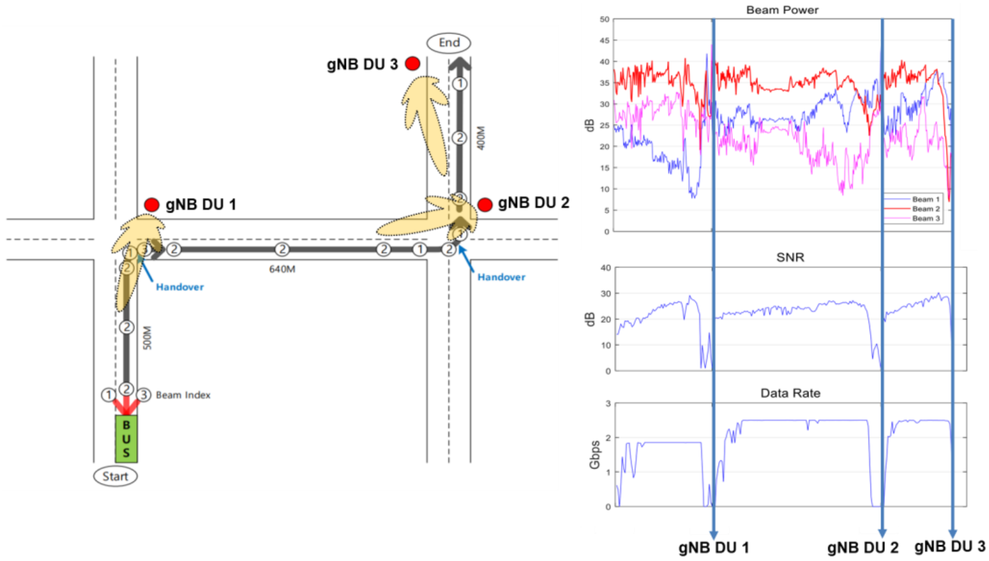


Figure 89: Measured receive SNR and downlink data rate of PHY-to-PHY testing in Daejeon city, south Korea

After the PHY-to-PHY test, system-level integration and preliminary field trial were performed in October 2020. The physical layer was integrated with system components corresponding to L2/L3 and 5G core functionalities, and a field trial with the integrated system was conducted on the road in ETRI premises (same location as shown inFigure 89), showing that onboard passengers with smartphones can connect with onboard Wi-Fi and access Youtube for high-quality video streaming. While the vehicle is moving, video streaming was very stable and no interruption was observed. In addition, by using an Internet speed testing application called BenchBee, it was estimated that an onboard Wi-Fi connection is capable of providing downlink data rates of up to 400 Mbps.

Lastly, at the end of November 2020, as shown inFigure 90, ETRI conducted a field trial on a highway test track in Yeoju, Korea. The field trial was conducted using an mmWave OBU (vehicle UE) installed on the demo bus and network equipment including 5G core and five gNB DUs deployed along the trackside as shown in the figure. The results of the field trial are also provided in Figure 90. It can be seen that the measured SNR ranges from 7 dB to 30 dB and is decreased with the distance between the DU and vehicle, obviously due to the increased path loss. We also measured both the downlink data rate of the link between gNB DU and vehicle UE and the onboard Wi-Fi data rate. From the figure, it can be observed that at least 1:15 Gbps of data rate is achievable for 90% of the time during the test and that the Wi-Fi data rate that can be provided to a smartphone was measured to be over 400 Mbps. In summary, during the final field on the Yeoju highway, it was observed that all the functionalities work as expected, which allowed us to successfully demonstrate our US, Tethering via Vehicle, in which broadband onboard Wi-Fi services are provided to onboard passengers.

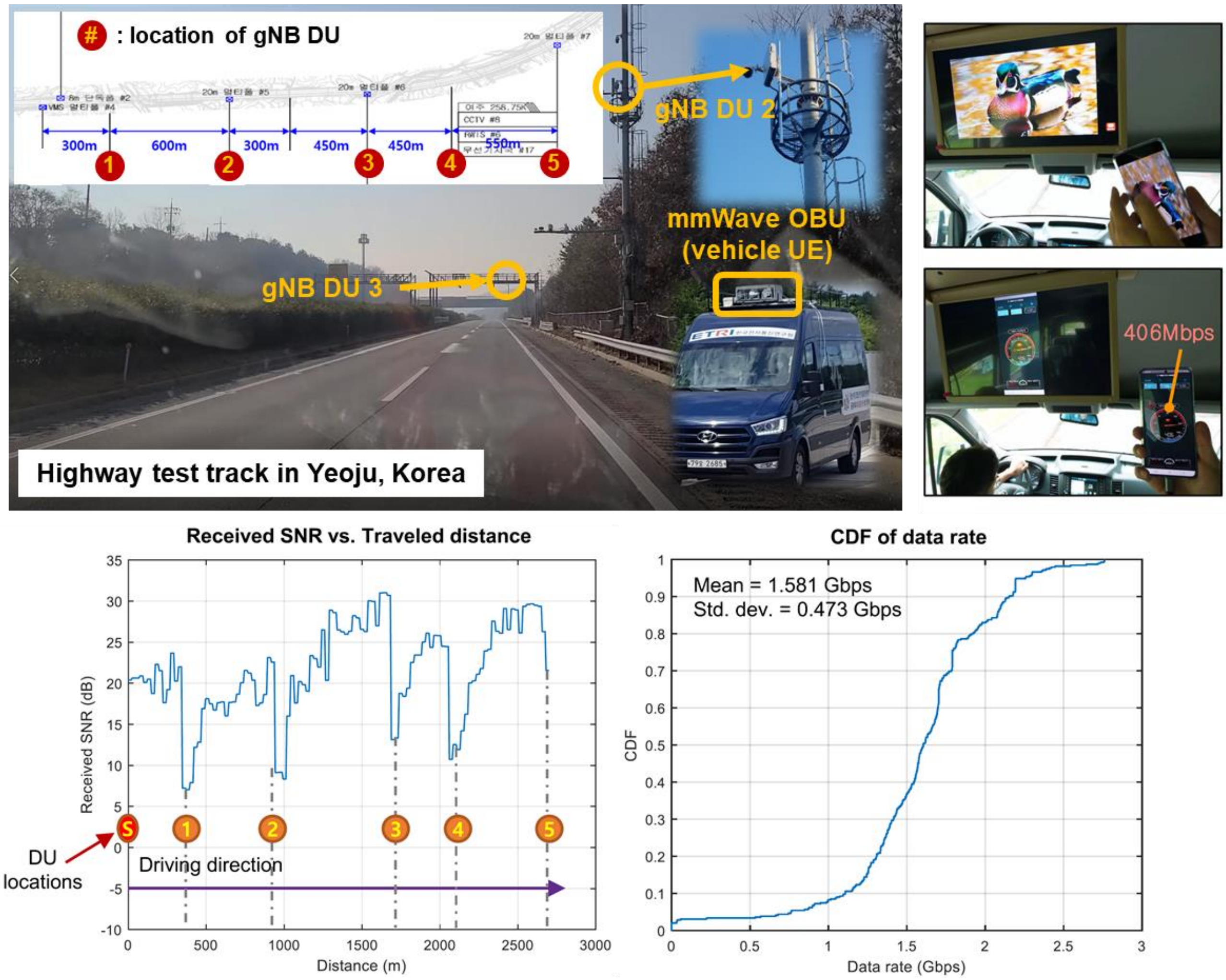


Figure 90: Field trial conducted on a highway test track in Yeoju, Korea

11.5 KR Deployment Challenges & Lessons Learned

In KR TS, mmWave 5G NR communication system has been developed, and as previously mentioned, a field trial on a highway was conducted with the system for demonstration of the US, Tethering via Vehicle. While the demonstration is successful in the sense that key functionalities such as beam switching and handover were validated and performance requirements of the US were met, two challenges were identified during the field trial from a deployment perspective. The first challenge observed is signal blockage by the road bridge (see Figure 91) located between gNB DU 2 and DU 3, which resulted in unreliable communication in some regions, especially just before the vehicle UE enters the road bridge. To confirm this phenomenon, we conducted an additional ray-tracing simulation in which the same environment as the test site is constructed to extract channel qualities. As shown in Figure 91, by comparing the cases with and without the road bridge, it was confirmed that a very serious received power loss occurred in the NLOS region before the bridge. The result gives an insight that in which a road bridge exists, a gNB DU should be deployed lower than the bridge or much higher than and close to the bridge.

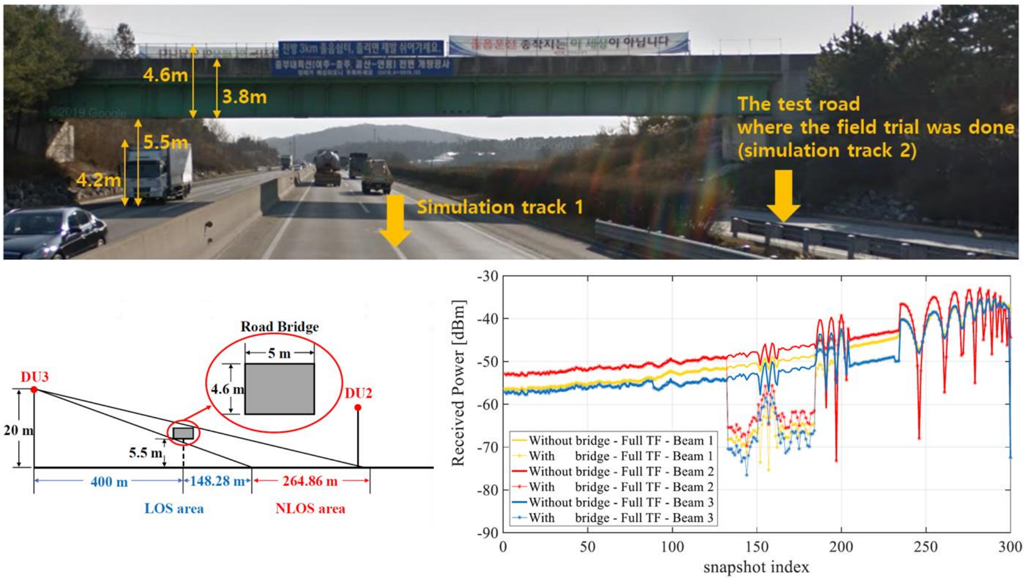


Figure 91: Deployment challenge – signal blockage by a road bridge

The other challenge observed during the field test was a strong interference from adjacent cells, which has serious interference effects on the reception of the serving cell signal. Although this was not a critical issue for our field trial with one vehicle UE, this needs to be addressed before the commercial version of the system, in which multi-UE communication scenarios are implemented, is rolled out. To solve this problem, it is necessary to investigate different frequency planning strategies or inter-gNB DU scheduling/resource allocation mechanisms to mitigate the interference effect.

12. CONCLUSION & RECOMMENDATIONS

12.1 Key Challenges for Cross-Border 5G-enabled CAM Service Deployments

Key challenges that were observed during 5G-enabled CAM service deployment efforts can be classified into 3 major categories, namely technical challenges, legal and regulatory challenges as well as reliability and availability challenges.

In terms of technical challenges, physical implementation issues, optimisation and configuration challenges, cross-network interconnectivity issues, seamless roaming activities and device/infrastructure availability can be mentioned. Physical implementation issues were among the few issues that were encountered during field tests. During the project MNOs commercial LTE network antennas were used as NR anchoring for different networks at CBCs. Some physical adjustments had to be made since there was an overshoot to undesirable places. On the other hand, as instant roaming between different MNOs means seamless communication for applications, long disconnection times of current network did not enable seamless cross-border CAM services. Furthermore, MNOs that support roaming were interconnected through IPX/GRX networks so that subscribers of both MNOs can obtain services from the visited network and related roaming traffic traverses through IPX/GRX networks, which are optimum designed for traditional services (i.e. voice, data) with exchange hubs deployed at specific main geographical locations. However, in order to fulfil the strict latency requirements imposed by the CAM use cases supported at the GR-TR cross-border trials, it was decided that the networks of Cosmote and Turkcell would be interconnected directly via a leased line. Regarding ES-PT CBC, it was necessary to provide maximum performance in terms of bandwidth and latency to vehicles, so initially it was decided to support the 5G anchoring in all the 4G bands in the border of Spain and Portugal, but when the first field tests were conducted it was discovered that coverages was very extensive. It was observed that 4G band layer the handover procedure starts in very distant points, but in some cases even several kilometers away from the border of the two counties. Moreover, performance relied on the commercial network concurrency, so at peak hours test results were affected significantly by the network.

Another technical challenge was faced during the testing of seamless inter PLMN switching with dual modems. During these trials it was observed that the backup network interface was immediately running when one UE was temporarily disabled. IP visibility was another challenge in CAM deployments with inter- and intra-MNO UE usage due to the UDP socket-based communication of UEs that are at the same area for same/different MNOs. The IPX/GRX providers allow MNOs and other service providers to efficiently connect their IP based networks to achieve roaming and inter-working between them. However, it was discovered that the current IPX/GRX networks increase latency drastically because exchange hubs of operator delivery services were not optimized in terms of geographical distribution. Furthermore, transmission power and coverage optimization at CBC sites was another challenge for successful RAN deployments to avoid interference and coverage gaps at border locations. Considering the project timeline and the duration of activities ensuring the robustness of equipment (e.g., OBU, sensors, etc.) through various temperature and weather conditions was imperative for the installation/set-up procedures and validation tests. Also, delays were experienced in some local testing activities due to the scarcity of 5G chipsets and modules such as SA/NSA mode devices or OBUs. This can also be stemmed from the limited available support and experience from the 5G ecosystem.

Legal and regulatory challenges included temporal permission for experimental networks, PLMN-ID restrictions and spectrum license availability. In certain sites, spectrum licenses were key enablers for institutional testbed networks. However, as the licenses were for research purposes, there was more stringent restrictions on geographical coverage and available bandwidth (for CAM use cases). For 5G license, the FI-TS had access to 60 MHz spectrum in n78 3.5 GHz TDD band (rather than usual 100 MHz or more, that is usually allocated to commercial operators in Finland). Another restriction was on the number of allocated PLMN-IDs. The increase in demand for PLMN-IDs for private 5G networks seems to add to scarcity of PLMN-IDs e.g., AALTO was assigned 10 PLMN-IDs when project started, but this was later reduced to two PLMN-IDs, which limits the number of PLMNs that could be activated in the test site. Moreover, the regulations also provided restrictions on TDD frame structure, with need for harmonized and synchronized frame structures to minimize the interference. On the other hand, experimentation in DE TS was forced to temporal operation with the experimental network that used the idle bands. Tight regulations, and complicated procedures with public institutions required detailed prototype equipment working in a specific band that is agreed after an initial study. In some cases, the permission ended after some months, and it was dependent on arranged or unexpected commercial auctions.

Reliability and availability challenges were also observed during the 5G-enabled development and deployment efforts. Degrading QoE, server disconnections or connection failures were among the challenges due to the packet losses and average DL/UL BW availabilities. Overall, big latencies were observed with MEC infrastructure components. Furthermore, 5G and LTE mode instabilities were faced due to the available network deployments avoiding ping-pong switching between 5G/LTE modes. Furthermore, TSs had to contend with the scarcity of 5G chipsets and modules, which resulted in delays in testing and trialing activities. There were also regional variations observed in commercial SA devices. For instance, it was noted that Samsung S20 in US supports SA, while a similar device sold in Europe does not work on SA mode. Additionally, restrictions were also noted on the PLMN-IDs that were supportable by SA devices. Conducting experiments over the lifespan of deployment efforts required robustness of equipment and infrastructure components against various technical and environmental factors such as temperature changes, weather conditions, device update requirements and interconnections of diverse technologies.

Other non-technical issues included project workers requiring visa at border crossings of GR-TR CBC. Issuing of a visa is a time-consuming procedure and Visa applications should have been made quite in advance. Delays at border crossings are inevitable, not only due to the Covid-19 pandemic, but also due to the corridor’s important and intensive use in terms of commercial transportation. While the project tests are being conducted, the police and military authorities must be informed before the border crossing. The authorities in the project organization have made great efforts on the subject and have helped to solve many problems. However, although these permits were obtained, a lot of time was lost during border crossings due to various coordination problems. The difficulty of carrying out such projects in high security areas was seen in this Project.

12.2 Best Practices for Cross-Border Deployments

Operational and management efforts from all trial site partners resulted in valuable lessons and best practices for future cross-border deployments. A technical best practice from CBCs was to jointly fine tune RAN parameters with their thresholds from both border sites in order to avoid undesirable transfers and ping-pong effects on nearby towns while ensuring smooth handovers in a synchronised manner. Another key take away was not to take the support of 5G OBUs and other vehicular connectivity devices for granted in multi-PLMN environments especially for relatively immature SA-mode devices. This was observed when SA devices were supporting known commercial PLMN-IDs and did not work with PLMN-IDs allocated for non-commercial test networks. Regarding V2X deployments in networks with several PLMNs some implications can occur when some of the bands are configured with multiple PLMNs, as a reconfiguration on one PLMN may affect other PLMNs as a side-effect. Having nodes configured with several PLMNs using specific configuration in some bands should be independent on the configuration on other bands.

Other technical best practices included dual Modem and MEC service usage with UEs based on signal intensity and GPS positioning for the assisted roaming applications. This helped with testing activities of seamless roaming applications when current networks did not support cross-border CAM services due to long disconnection times. Another best practice for vehicles that do not know the address of the MEC and cannot connect to it was discovered. A MEC Registry deployed in the cloud was utilized for compiling available MECs. Additionally, a MEC orchestrator deployed in each MEC was used to manage MEC Handover and data synchronization. Experimentations with slicing techniques has been shown to be effective for guaranteeing the connectivity of V2X traffic and applications during congestion. The configuration can be scaled up to (much) more than two slices. However, the dimensioning and the distribution of the capacities between the slices serving different groups of application and users through absolute and relative priorities will become complex.

A best practice for increasing the reliability and availability in trial sites was to incorporate QoS adaptation. Resultingly, server disconnections and packet losses were managed where the UL and DL BW was fluctuating and heavily affected. The 5G-MOBIX common data formats have been defined rather later stage of the project, although the developments of components and software modules have been started much earlier. Once common data formats have been finalised, it became clear that, in order to obtain complete logs at different communication layers, we had to not only to use multiple data sources but also those sources had to provide data with various formats, obviously different from the common data format. This created a challenge particularly in developing an automatic data analysis tool because it needed to handle various files with largely different formats and sizes.

CAM applications use interchange messages between vehicles that are sharing physical space while connected to different networks located in separate countries. If messages are interchanged using Internet connections between countries, there will be an additional delay of several tens of milliseconds. Dedicated direct connections between the borders of the countries where vehicles are moving seems to be required to connect MEC applications and 5G Cores. Diversity of scenarios in the roads that connect countries may require different bands for anchoring the 5G NSA networks. The selected bands are very relevant to customize the handover radio events and the location where the handover change take place in optimal solutions. Coexistence with commercial networks for automotive CAM applications and conventional mobile services may require extra effort to customize the radio network and isolate both networks when one of them is overloaded. The use of slices to isolate in the most efficient manner both networks seem to be highly recommended.

12.3 Future Directions

In future projects, it seems necessary to define common data formats at the earlier stages of the project, so that the component developments and deployments can be made for generating data that align with (as much as possible) the common data formats. Another important feature for CAM applications would be to include more automation in future development and deployment efforts. MNOs often need to exchange ARFCN and PCI information of neighbouring cells. Therefore, the base stations at the borders need to be configured with special configurations, changing over time as the network evolves. Another improvement regarding slice management can be done by focusing on resource separation techniques for the resources allocated to CAM services in radio, transport, and cloud slices since the impact of CAM applications is expected to increase in the future alongside with the availability of V2X technologies. Finally, a cautionary item for future work on 5G-enabled cross-border CAM services, is that even though certain 5G features that have the potential to boost performance, have been standardized, their actual deployment, configuration and use in real -life conditions and networks is not an easy task, as even world-leading vendors may not have all implementations available. Usually, vendors use a strict prioritization plan based on the most useful features (the ones that the markets prioritize), thus not all standardized features are available for deployment.

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13. ANNEX 1 – ES-PT MEASUREMENTS & ANALYSIS

This annex presents agnostic and relevant results at ES-PT CBC (New and Old bridge) using a single OBU-5G Modem. Tests have been done with different SIM card, once with ES SIM card from Nokia and other with PT SIM card from NOS.

ES Side Results

The following tables shows the data rate reference for the UDP TC. The transmission data rate will be defined as 20% over the result obtained in TCP case. For every KPI which have TCP and UDP iterations, the reference for the UDP case is the obtained value for the TCP case. For KPI which have only UDP iterations, the reference used will be the KPI AG1/AG2.

Calculated rate for UDP protocol from average results of TCP KPI AG1:

SITE NAME	Average AG1 (Throughput DL TCP)	Reference (20% over TCP)
A-55	344.31 Mbps	413.172 Mbps
NEW BRIDGE	288.84 Mbps	346.608 Mbps
OLD BRIDGE	364.29 Mbps	437.148 Mbps
CTAG'S TEST TRACKS	352.98 Mbps	423.576 Mbps

Calculated rate for UDP protocol from average results of TCP KPI AG2:

SITE NAME	Average AG1 (Throughput DL TCP)	Reference (20% over TCP)
A-55	75.099 Mbps	90.119 Mbps
NEW BRIDGE	77.053 Mbps	92.464 Mbps
OLD BRIDGE	62.833 Mbps	75.400 Mbps
CTAG'S TEST TRACKS	61.444 Mbps	73.733 Mbps

Calculated rate for UDP protocol from average results of KPI AG3:

SITE NAME	Average AG3 (Throughput DL TCP)	Reference (20% over TCP)
A-55	258.066 Mbps	309.679 Mbps
NEW BRIDGE	162.546 Mbps	195.055 Mbps
OLD BRIDGE	172.116 Mbps	206.539 Mbps
CTAG'S TEST TRACKS	200.88 Mbps	241.056Mbps

Calculated rate for UDP protocol from average results of TCP KPI AG4:

SITE NAME	Average AG1 (Throughput DL TCP)	Reference (20% over TCP)
A-55	40.492 Mbps	48.590 Mbps
NEW BRIDGE	23.828 Mbps	28.594 Mbps
OLD BRIDGE	15.119 Mbps	18.143 Mbps
CTAG'S TEST TRACKS	61.444 Mbps	73.733 Mbps

Test Location	Old Bridge	**Test Case (TC) ID**	KPI_AG1
Test Case (TC) Name	DL Data Throughput of Single User (Mbps) – stationary / Central		
Test Case Purpose	Measure the maximum, minimum and average TCP DL throughput under the best RF conditions in over 1 minute.		
Stationary / Mobility TC	Stationary		
Test environment	Old Bridge		
Test setup ID	ES_Scheme_01		
5G Deployment Option	NSA (option 3x)		
PLMN ID (MCC + MNC)	214 38		
Test UE Info			
UE Type: Quetel RM500Q-GL *UE category: Modem* *UE SW version: RM500QGLABR11A06M4G* *UE Type: OBU* *UE category: HMCU 5G EVB* *UE SW version: v 1.2_5G* *UE speed: 0 km/h*			
Test Variables			
Live NW traffic on the transmission link. Moving vehicles.			
Expected TC Result			
Obtained maximum DL throughput. Values about 500Mbps was obtained using a mobile phone.			
TC Results Report			
Number of repetitions	3		
TC comments	*TCP protocol. DL throughput. Best RF conditions. 1 minute long.*		
Tools used	*iperf*		
TC Logs	*Folder with the logs for the three iterations, both access and network:* • *accessaggr_KPI_AG1_TCP_01_.csv* • *accessaggr_KPI_AG1_TCP_02_.csv*		

	• *accessaggr_KPI_AG1_TCP_03_.csv* • *networkaggr_KPI_AG1_TCP_01_.csv* • *networkaggr_KPI_AG1_TCP_02_.csv* • *networkaggr_KPI_AG1_TCP_03_.csv*			
Test Results	Iteration #1	Iteration #2	Iteration #3	Descriptions/Diagrams
Max throughput (Mbps)	471.838	409.177	424.271	Figure 92 represents a comparison between the three iterations. Also indicates the value of RSRP.
Min throughput (Mbps)	256.577	229.212	259.567	
Average throughput (Mbps)	354.416	364.718	373.221	
10th Percentile throughput (Mbps)	305.65	323.61	343.5	
90th Percentile throughput (Mbps)	390.84	403.16	404	
Average Spectral Efficiency (b/s/Hz)	8.860	9.118	9.331	
TC Responsible	*CTAG*			
Date	*22/02/2022*			

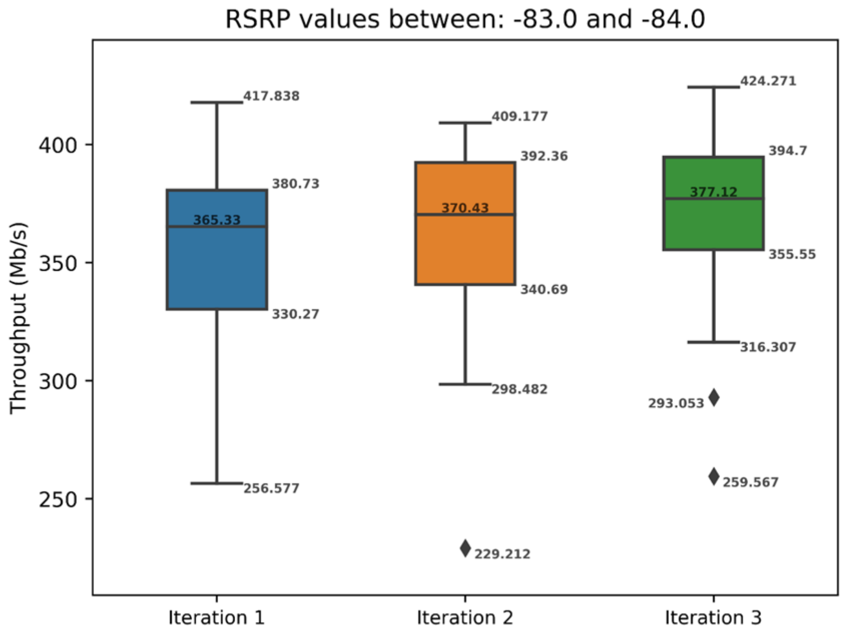

Figure 92: Throughput comparison between three iterations KPI_AG1 DL TCP in Old Bridge

Figure 93: Point of measurement in perspective with the antenna. Old Bridge

Test Location	Old Bridge	**Test Case (TC) ID**	KPI_AG2
Test Case (TC) Name	UL Data Throughput of Single User (Mbps) - stationary / Central		
Test Case Purpose	Measure the maximum, minimum and average TCP UL throughput under the best RF conditions in over 1 minute.		
Stationary / Mobility TC	Stationary		
Test environment	Old Bridge		
Test setup ID	ES_Scheme_01		
5G Deployment Option	NSA (option 3x)		
PLMN ID (MCC + MNC)	214 38		
Test UE Info			
UE Type: Quetel RM500Q-GL *UE category: Modem* *UE SW version: RM500QGLABR11A06M4G* *UE Type: OBU* *UE category: HMCU 5G EVB* *UE SW version: v 1.2_5G* *UE speed: 0 km/h*			
Test Variables			
Live NW traffic on the transmission link. Moving vehicles.			
Expected TC Result			
Obtained maximum DL throughput. Values about 65Mbps was obtained using a mobile phone.			
TC Results Report			
Number of repetitions	3		
TC comments	*TCP protocol. UL throughput. Best RF conditions. 1 minute long.*		
Tools used	*iperf*		
TC Logs	*Folder with the logs for the two iterations, both access and network:*		

	• *accessaggr_KPI_AG2_TCP_01_.csv* • *accessaggr_KPI_AG2_TCP_02_.csv* • *accessaggr_KPI_AG2_TCP_03_.csv* • *networkaggr_KPI_AG2_TCP_01_.csv* • *networkaggr_KPI_AG2_TCP_02_.csv* • *networkaggr_KPI_AG2_TCP_03_.csv*			
Test Results	Iteration #1	Iteration #2	Iteration #3	Descriptions/Diagrams
Max throughput (Mbps)	91.985	84.063	90.711	Figure 94represents a comparison between the three iterations. Also indicates the value of RSRP.
Min throughput (Mbps)	50.334	43.056	50.327	
Average throughput (Mbps)	62.819	63.789	61.892	
10th Percentile throughput (Mbps)	53.57	52.72	52.92	
90th Percentile throughput (Mbps)	75.03	75.18	75.67	
Average Spectral Efficiency (b/s/Hz)	1.57	1.595	1.547	
TC Responsible	*CTAG*			
Date	*21/02/2022*			

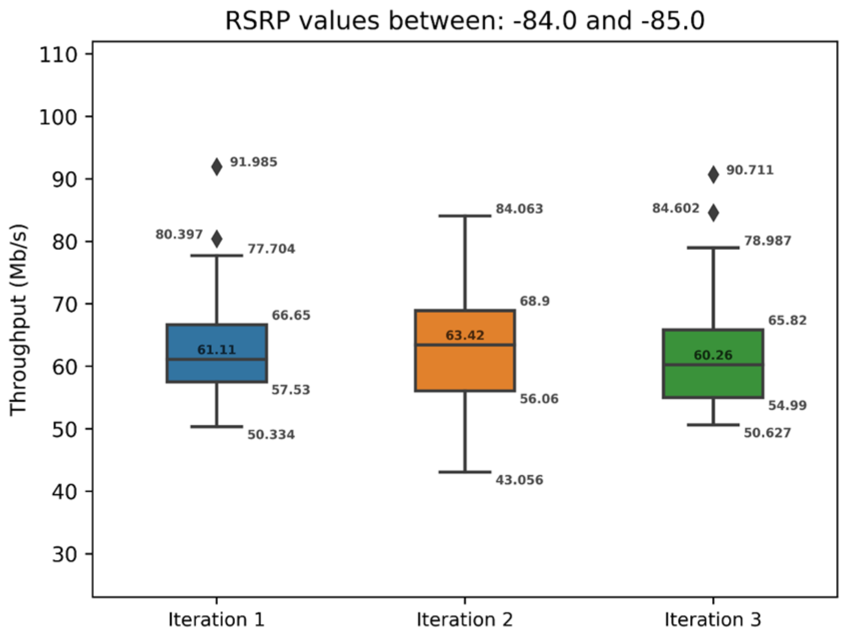

Figure 94: Throughput comparison between three iterations KPI_AG2 UL TCP in Old Bridge

PT Side Results

The following tables shows the data rate reference for the UDP TC. The transmission data rate will be defined as 20% over the result obtained in TCP case.

For KPI which have TCP and UDP iterations, the reference for the UDP case is the obtained value for the TCP case.

For KPI which have only UDP iterations, the reference used will be the KPI AG1/AG2.

Calculated rate for UDP protocol from average results of TCP KPI AG1:

SITE NAME	Average AG1 (Throughput DL TCP)	Reference
NEW BRIDGE	370.414 Mbps	444.497 Mbps
OLD BRIDGE	477.275 Mbps	572.73 Mbps
A28	233.28 Mbps	279.94 Mbps

Calculated rate for UDP protocol from average results of TCP KPI AG2:

SITE NAME	Average AG1 (Throughput DL TCP)	Reference
NEW BRIDGE	155.883 Mbps	187.06 Mbps
OLD BRIDGE	107.578 Mbps	129.094 Mbps
A28	97.14 Mbps	109.37 Mbps

Calculated rate for UDP protocol from average results of KPI AG3:

SITE NAME	Average AG3 (Throughput DL TCP)	Reference
NEW BRIDGE	156.681 Mbps	188.017 Mbps
OLD BRIDGE	10.81 Mbps	12.972 Mbps
A28	197.023 Mbps	236.43 Mbps

Calculated rate for UDP protocol from average results of TCP KPI AG4:

SITE NAME	Average AG1 (Throughput DL TCP)	Reference
NEW BRIDGE	28.602 Mbps	34.322 Mbps
OLD BRIDGE	19.143 Mbps	22.972 Mbps
A28	9.57 Mbps	11.48 Mbps

Test Location	New Bridge	Test Case (TC) ID	KPI_AG3
Test Case (TC) Name	DL Data Throughput of Single User (Mbps) - stationary / Cell Edge		

Test Case Purpose	Measure the maximum, minimum and average TCP DL throughput under the worst RF conditions in over 1 minute.
Stationary / Mobility TC	Stationary
Test environment	New Bridge
Test setup ID	PT_Scheme_01
5G Deployment Option	NSA (option 3x)
PLMN ID (MCC + MNC)	268 93
Test UE Info	
UE Type: Quetel RM500Q-GL *UE category: Modem* *UE SW version: RM500QGLABR11A06M4G* *UE Type: OBU* *UE category: HMCU 5G EVB* *UE SW version: v 1.2_5G* *UE speed: 0 km/h*	
Test Variables	
Live NW traffic on the transmission link. Moving vehicles.	
Expected TC Result	
Obtained maximum DL throughput.	
TC Results Report	
Number of repetitions	3
TC comments	*TCP protocol. DL throughput. Worst RF conditions. 1 minute long.*
Tools used	*iperf*
TC Logs	*Folder with the logs for the three iterations, both access and network:*

Test Results	Iteration #1	Iteration #2	Iteration #3	Descriptions/Diagrams
Max throughput (Mbps)	241.505	235.773	220.981	Figure 95 represents a comparison between the three iterations. Also indicates the value of RSRP.
Min throughput (Mbps)	100.029	71.527	72.961	
Average throughput (Mbps)	160.691	157.506	151.846	
10th Percentile throughput (Mbps)	122.87	94.27	87.62	
90th Percentile throughput (Mbps)	191.47	193.85	192.16	
Average Spectral Efficiency (b/s/Hz)	4.017	3.94	3.796	
TC Responsible	*CTAG*			
Date	*09/03/2022*			

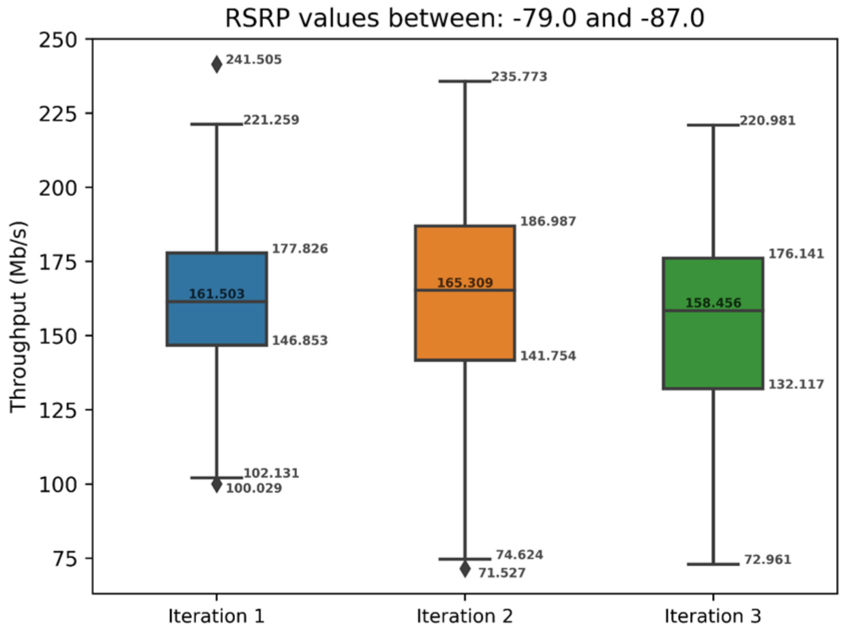

Figure 95: Throughput comparison between three iterations KPI_AG3 DL TCP in New Bridge

Figure 96: Point of measurement in perspective with the antenna. New Bridge

Test Location	New Bridge	Test Case (TC) ID	KPI_AG4
Test Case (TC) Name	UL Data Throughput of Single User (Mbps) - stationary / Cell Edge		
Test Case Purpose	Measure the maximum, minimum and average TCP UL throughput under the worst RF conditions in over 1 minute.		
Stationary / Mobility TC	Stationary		
Test environment	New Bridge		
Test setup ID	PT_Scheme_01		
5G Deployment Option	NSA (option 3x)		
PLMN ID (MCC + MNC)	268 93		
Test UE Info			

UE Type: Quetel RM500Q-GL *UE category: Modem* *UE SW version: RM500QGLABR11A06M4G* *UE Type: OBU* *UE category: HMCU 5G EVB* *UE SW version: v 1.2_5G* *UE speed: 0 km/h*				
Test Variables				
Live NW traffic on the transmission link. Moving vehicles.				
Expected TC Result				
Obtained maximum UL throughput.				
TC Results Report				
Number of repetitions	3			
TC comments	*TCP protocol. UL throughput. Worst RF conditions. 1 minute long.*			
Tools used	*iperf*			
TC Logs	*Folder with the logs for the three iterations, both access and network:*			
Test Results	**Iteration #1**	**Iteration #2**	**Iteration #3**	**Descriptions/Diagrams**
Max throughput (Mbps)	75.183	55.499	44.937	Figure 97 represents a comparison between the three iterations. Also indicates the value of RSRP.
Min throughput (Mbps)	10.786	12.527	17.25	
Average throughput (Mbps)	28.941	31.613	25.253	
10th Percentile throughput (Mbps)	14.93	19.88	20.35	
90th Percentile throughput (Mbps)	47.3	41.69	33.92	
Average Spectral Efficiency (b/s/Hz)	0.724	0.79	0.631	
TC Responsible	*CTAG*			
Date	*09/03/2022*			

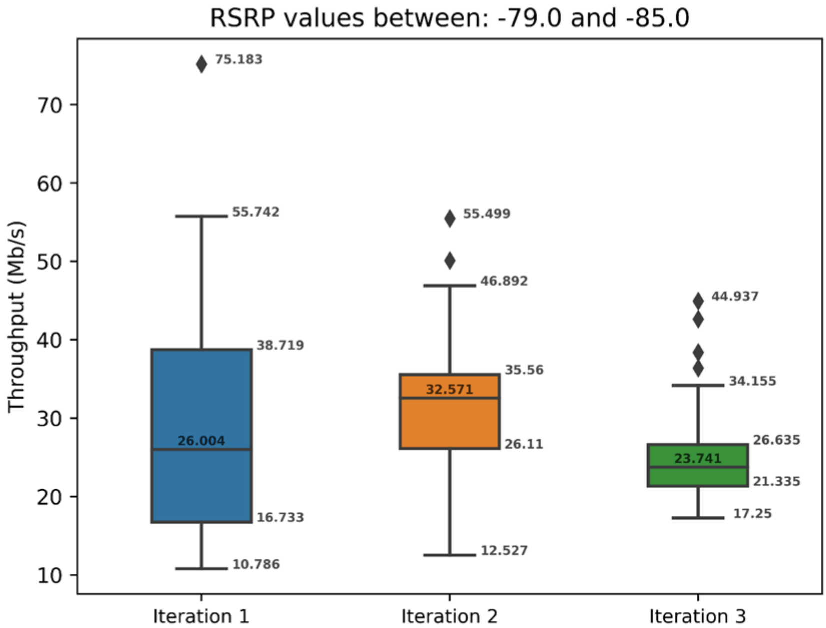

Figure 97: Throughput comparison between three iterations KPI_AG4 DL TCP in New Bridge

Whole report for ES-PT CBC: 5G-MOBIX-D3.7-appendices-v0.2-ES-PT_CTAG.docx

This report presents all the results at ES-PT CBC in the six available antennas (A-55, CTAG's test tracks, New Bridge ES side, Old Bridge ES side, New Bridge PT side and Old Bridge ES side) for the nine mandatory KPIs (KPI_AG1 to KPI_AG9).

Conclusion

The following are the conclusions of the results of the agnostic tests for the ES-PT CBC.

First of all, take a look at points *Antenna locations and coverage (Spanish side)* (page 22) and *Antenna locations and coverage (Portuguese side)* (page 26) of the 5G-MOBIX - D3.7 -appendices - v0.2 - ES-PT_CTAG.docx (sharepoint.com) to situate the seven involucrate antennas.

And before starting with the explanation, two topics must be kept in mind during the conclusions reading.

First, notice that both 4G and 5G have been considered during the tests, since the network is controlled by 4G because it is NSA.

Last, as explained in the point *UDP upload test problem* (page 23) of the 5G-MOBIX - D3.7 -appendices - v0.2 - ES-PT_CTAG.docx (sharepoint.com) in UL UDP tests there was a loss of connectivity that prevents transmission at high rates. This problem has a direct impact on the tests results since it is not possible to transmit at the required rate because the connection to the network is lost. It is necessary to reduce the transmission rate to a value that does not cause a loss of connection.

Static DL throughput in central edge coverage (AG1)

The better throughput values are obtained in for the Old Bridge PT antenna (approx. 500 Mbps in TCP and 550 Mbps in UDP), and the worst values are obtained for the A28 antenna (approx. 250 Mbps). The other antennas have almost the same values (approx. 350 Mbps in TCP and 400 Mbps in UDP).

Table 58: Static DL throughput in central edge coverage (AG1)

	A-55	CTAG's test tracks	Old Bridge ES	New Bridge ES	Old Bridge PT	New Bridge PT	A28
AG1 – DL Throughput Central Edge – Average Mbps	TCP: 344.32 UDP: 415.97	TCP: 352.99 UDP: 396.46	TCP: 364.12 UDP: 412.09	TCP: 344.32 UDP: 347.03	TCP: 477.27 UDP: 556.46	TCP: 370.41 UDP: 371.19	TCP: 313.93 UDP: 246.38

The throughput TCP values are lower than the throughput UDP values, which is a correct result, because UDP protocol is faster than TCP protocol.

UDP protocol allows a higher transfer speed than TCP protocol because it does not have a back-and-forth verification system between the transmitting device and the receiving device, as TCP has. For this reason, the UDP protocol is the most widely used for services where the speed of transmission is more important than a possible loss of data.

On the other hand, TCP protocol is more reliable than UDP protocol, because TCP establishes a connection between a sender and receiver before data can be sent, and UDP, by contrast, does not establish a connection before sending data. And because of the back-and-forth verification system between the transmitting device and the receiving device.

Static DL throughput in cell edge coverage (AG3)

The better throughput values are obtained in for the A-55 antenna (approx. 250 Mbps in TCP and 300 Mbps in UDP), and the worst values are obtained for the Old Bridge PT antenna in TCP (approx. 65 Mbps) and for the A28 antenna in UDP (approx. 10 Mbps). The other antennas have almost the same values (approx. 170 Mbps in TCP and 200 Mbps in UDP).

Table 59: Static DL throughput in cell edge coverage (AG3)

	A-55	CTAG's test tracks	Old Bridge ES	New Bridge ES	Old Bridge PT	New Bridge PT	A28
AG1 – DL Throughput Cell Edge – Average Mbps	TCP: 258.07 UDP: 305.07	TCP: 162.55 UDP: 169.47	TCP: 172.12 UDP: 171.55	TCP: 205.95 UDP: 206.99	TCP: 69.37 UDP: 10.69	TCP: 156.68 UDP: 10.81	TCP: 197.02 UDP: 166.67

With the worst coverage possible, TCP throughput values are lower than UDP throughput values for ES antennas, instead of PT antennas, in which TCP throughput values are higher than TCP throughput.

Static UL throughput (AG2, AG4)

The conclusions are the same as in the DL case, except for the UDP throughput values with cell edge coverage, where worst throughput values are for A28 antenna, followed by old bridge PT.

TCP mobility throughput (AG5, AG6)

The antenna with the highest difference from the better throughput value to the worst throughput value is the Old Bridge PT antenna, with approximately 520 Mbps of difference. The other antennas have similar differences, approximately 350 Mbps.

In this graphic it can be seen the throughput distribution for the Old Bridge PT antenna:

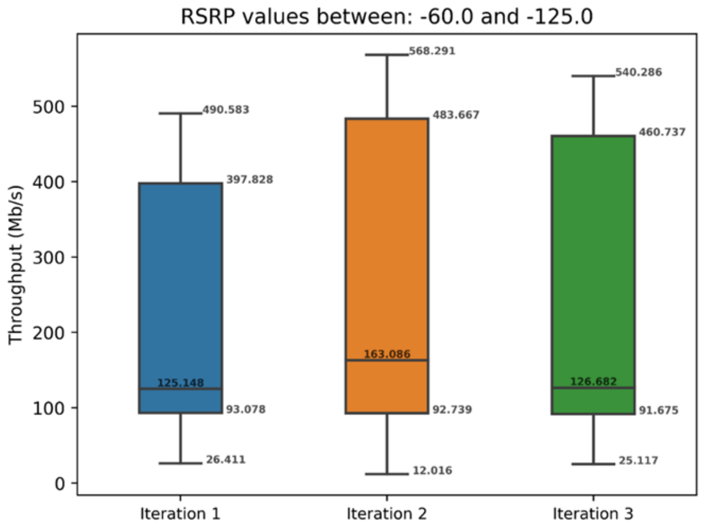

Figure 98: TCP mobility throughput for the old Bridge PT antenna

The following graphic represents the rest of the antennas, which have a similar throughput distribution:

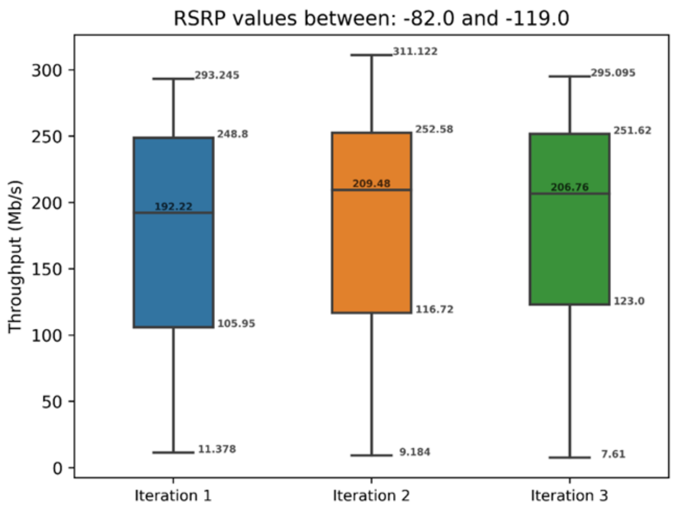

Figure 99: TCP mobility throughput for the old Bridge PT with rest of the antennas

UDP mobility packet loss (AG8, AG9)

The results indicate that the packet loss is higher in DL than in UL, but it is a normal result due to the problem on UL UDP tests. The transmission rate is lower than the capacity of the network, so the network is capable of processing all the information.

Latency (AG7)

The latency is higher in PT antennas than in ES antennas. The latency values are similar in the antennas within the same country, i.e., for ES antennas, with 32 bytes ping, latency is approximately 20 ms, and with 1400 bytes ping, latency is approximately 25 ms. For PT antennas, with 32 bytes ping, latency is approximately 65 ms, and with 1400 bytes ping, latency is approximately 35 ms.

ES antennas have a correct behaviour, because with a higher size ping, latency should be higher.

The tests were made in different days, so the behaviour is not conditioned by one day. This information is included in the following table:

Table 60: UDP mobility packet loss (AG8, AG9)

	A55	CTAG's test tracks	Old Bridge ES	New Bridge ES	Old Bridge PT	New Bridge PT	A28
Date	18/01	23/02	22/02	21/02	25/02	09/03	30/05
Latency 32 bytes	18.87	20.01	16.69	19.46	70.72	69.50	72.31
Latency 1400 bytes	24.18	25.36	25.33	24.49	51.63	50.24	55.42

Conclusion

As hypotheses that may justify certain discordant results, like the high latencies, or the higher latencies in PT antennas for lowest size ping than the latency for the highest size ping. Also, the results for static DL throughput in cell coverage for PT antennas, in which UDP throughput is lower than UDP throughput, it can be indicated:

- Test schedules are likely to be affecting the network load (as they are commercial).
- Different orientation of 4G and 5G antennas that can give very different values.
    - Coverage range of each antenna.

The coverage range of the antennas is an interesting topic, because it can be seen in the results, that Old Bridge PT antenna is the one that has the highest coverage range, from -60 dBm in the better case, to -117 dBm in the worst case. The coverage range of the other antennas reaches 40 dBm as the most.

The following graphics represent the comparison between coverage range of Old Bridge PT and A55 as representation of the rest of the antennas.

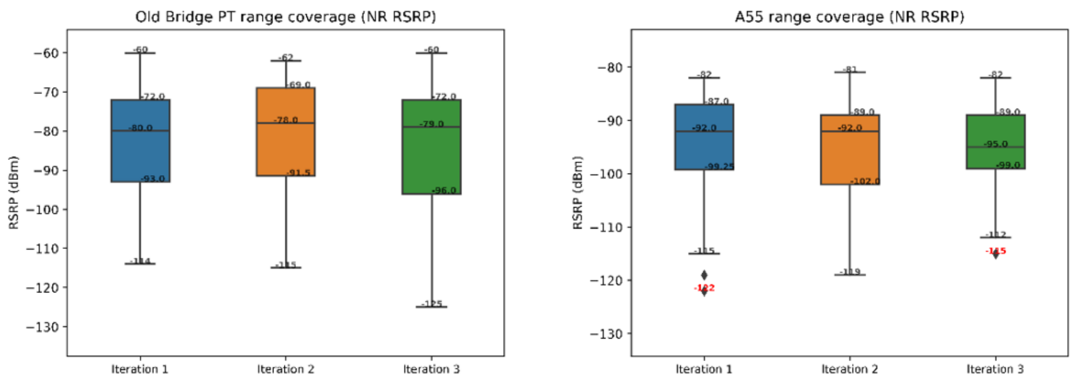

Figure 100: Comparison between coverage range of Old Bridge PT and A55 as representation of the rest of the antennas

14. ANNEX 2 – GR-TR MEASUREMENTS & ANALYSIS

Test Location	Kipi-Ipsala Border					
TC Name	HR with S1 HO and S10 Interface – Internet HR with S1 HO and S10 Interface – Direct Connection					
Trace route	GR-TR CBC between two country customs, see Figure 48					
TC parameters	CN Configuration					
						CS
TC Results Report						
Repetitions	4					
TC comments	Close to eNB/gNB locations UE get high throughput for Iteration one and two. When testing Home Routed direct connection scenario UE not able to get better throughput for these locations. Truck traffic also effect HO locations and user throughput performance. Therefore, the average throughput levels are different.					
Tools used	Huawei Prob tool and Huawei P40 UE					
Test Results	Iteration #1 (HR with Internet Connection) TR-GR	Iteration #2 (HR with Internet Connection) GR-TR	Iteration #3 (HR with Direct Connection) TR-GR	Iteration #4 (HR with Direct Connection) GR-TR		Total Average
Aver. Tput (Mbps)	447,12	525,67	203,5	247,4		355,9
Peak Tput (Mbps)	808,01	831,6	684,7	678,62		750,7
NR SS-RSRP (dBm) (max/min)	-78 -106	-75 -104	-72 -100	-72 -102		-74 -103
LTE RSRP (dBm) (max/min)	-77 -108	-70 -105	-79 -107	-79 -102		-76 -105
NR PCC DL Avg MCS	22	22	22	23		22
User Plane Interruption time LTE/NR (ms)	56/224	57/177	58/198	52/192		56/197
Vehicle Speed (avg/max) kmph	26 37					
TC Responsible	Turkcell - Ericsson					
Date	2021-12-25					
General comments and conclusions	Internet and direct connections are not affecting to user throughput level and user plane interruption time. See Figure 102 and Figure 103. More Details can be found in TCA-GR-TR-06_InterPLMN_HO_HR TCA-GR-TR-07_InterPLMN_HO_HR TCA-GR-TR-05_InterPLMN_HO_LBO page in the result report 5G-MOBIX - GR-TR_Agnostic_Test_Results.xlsx D3.7_Appendix-Results_GR-TR.					

Figure 101: Iteration one and two Inter PLMN HO locations

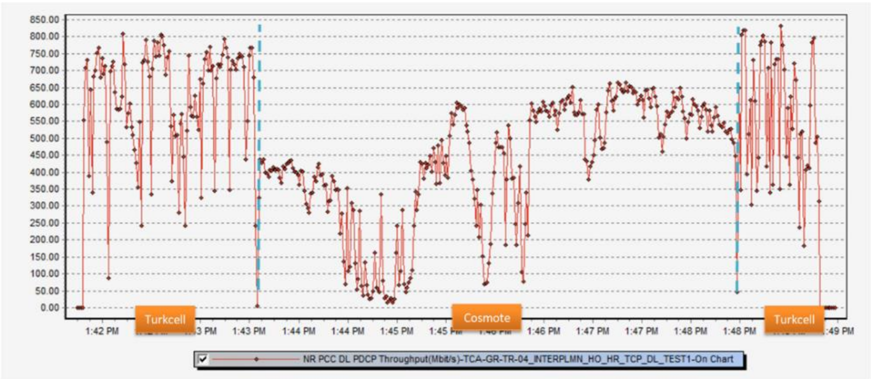

Figure 102: Sample PDCP DL throughputs performance for iteration 1 and 2

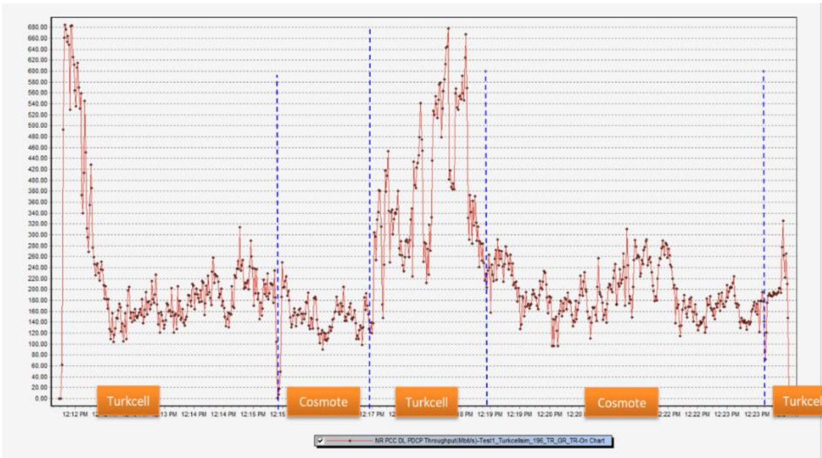

Figure 103: Sample PDCP DL throughputs performance for iteration 3 and 4

Test Location	Kipi-Ipsala Border						
TC Name	HR with S1 HO and S10 Interface – Internet/ Direct Connection LBO with S1 HO and S10 Interface – Direct Connection						
Trace route	GR-TR CBC between two country customs						
TC parameters	CN Configuration						
							CS
TC Results Report							
Repetitions	3						
TC comments	There were deviations in the measured values due to radio conditions. Inconsistent values were excluded from the calculations in order to make a meaningful comparison.						
Tools used	TEMS Investigation tool - Xiaomi MI10 UE						
Test Results	Iteration #1 (HR with Internet Connection)		Iteration #2 (HR with Direct Connection)		Iteration #3 (LBO with Direct Connection)		
	Home NW (GR)	Visited NW (TR)	Home NW (GR)	Visited NW (TR)	Home NW (GR)	Visited NW (TR)	Visited NW (TR)
Aver. Lat. (msec)	16,35	97,24	17,38	35,9	17,57	36,05	17,27
LTE SS-RSRP (dBm) (max/aver.)	-110 -100	-102 -90	-107 -99	-102 -90	-105 -98	-105 -92	-93 -90
NR RSRP (dBm) (max/aver)	-108 -97	-104 -93	-111 -101	-101 -89	-106 -102	-103 -93	-93 -91
Ping Size kbit	32	32	32				
Packet Loss Rate %	0,0786						
Date	3/30/2022 - 3/31/2022 - 5/13/2022						
General comments and conclusions	Every configuration change effected to latency values. • In the iteration 1 UE connected to home NW and RTT values measured 16,35 msec. After HO RTT values reached 97,24 msec level because of UE start to use s8 interface over the internet. • In the iteration 2 same HR configuration has tested with direct connection. After HO RTT values reduced from 97,24 msec to 35,9msec because of UE start to use s8 interface over direct leased line. • In iteration 3 LBO configuration has tested. After the HO UE maintained assigned IP from home network. After connection refresh UE get new IP from visited NW. RTT values almost same where UE in Home and Visited NW. More Details can be found in TCA-GR-TR-06_InterPLMN_HO_HR TCA-GR-TR-07_InterPLMN_HO_HR TCA-GR-TR-05_InterPLMN_HO_LBO page in the result report 5G-MOBIX - GR-TR_Agnostic_Test_Results.xlsx D3.7_Appendix-Results_GR-TR.						

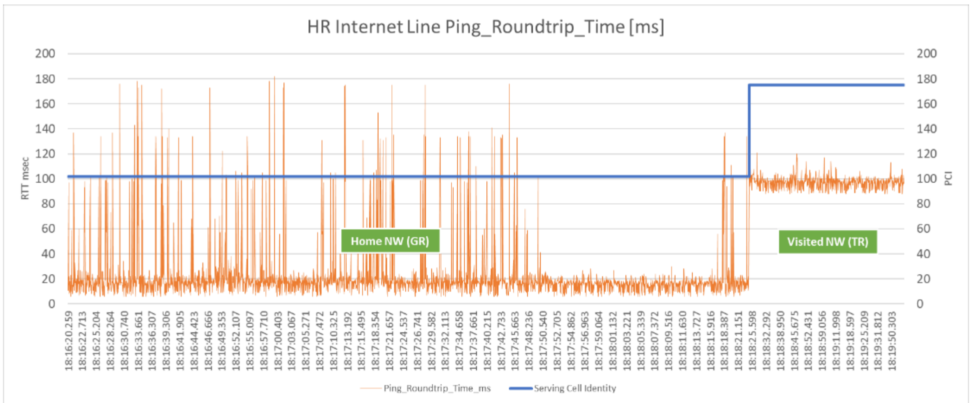

Figure 104: HR configuration - internet connection RTT performance

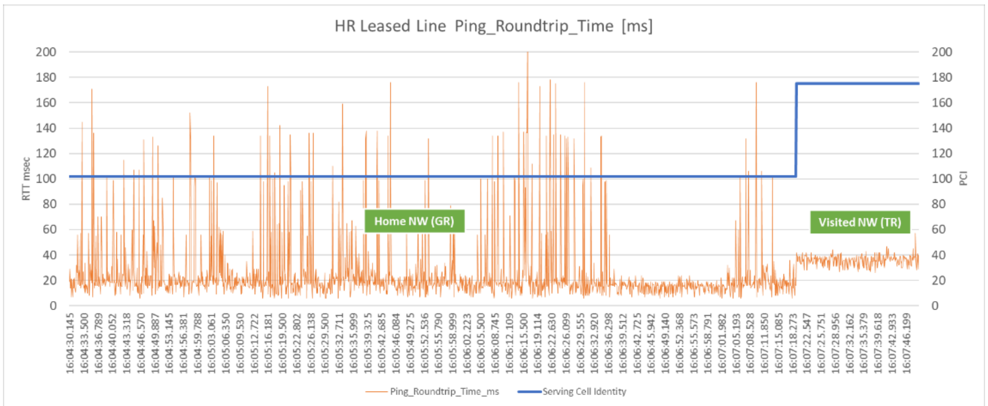

Figure 105: HR configuration - leased line connection RTT performance

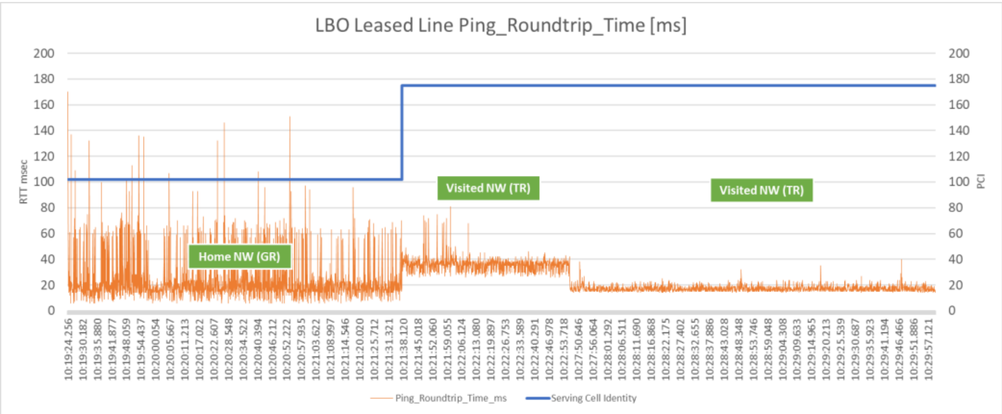

Figure 106: LBO configuration - leased line connection RTT performance

Test Location	Kipi-Ipsala Border	
TC Name	HR with S1 HO and S10 Interface Internet Connection HR with S1 HO and S10 Interface Direct Connection	
Trace route	GR-TR CBC between two country customs	
TC parameters	NW connectivity type between MNOs (Internet - Direct Connection)	
CS		
TC Results Report		
Repetitions	13	
TC comments		
Tools used	TEMS Investigation tool - Xiaomi MI10 UE	
Test Results	**LTE Interruption Time [ms]**	**NR Interruption time [ms]**
HR Internet Connection - TCP DL - Iteration-1	56	224
HR Internet Connection - TCP DL - Iteration-2	57	177
HR Internet Connection - TCP UL - Iteration-1	47	195
HR Internet Connection - TCP UL - Iteration-2	57	188
HR Direct Connection - TCP DL - Iteration-1	58	198
HR Direct Connection - TCP DL - Iteration-2	70	182
HR Direct Connection - TCP DL - Iteration-3	52	192
HR Direct Connection - TCP DL - Iteration-4	66	178
HR Direct Connection - TCP UL - Iteration-1	48	207
HR Direct Connection - TCP UL - Iteration-2	64	184
HR Direct Connection - TCP UL - Iteration-3	50	210
HR Direct Connection - TCP UL - Iteration-4	62	182
HR Direct Connection - TCP UL - Iteration-5	54	214
Date	3/30/2022 - 3/31/2022	
General comments and conclusions	Measurements were made depending on whether the connection between the operators is provided over the Internet or direct connection. Mobility Interruption time was measured from Turkey to Greece and from Greece to Turkey by applying TCP DL/UL tests. The change in interoperator connectivity had no effect on the measured KPI. In Figure 107 and Figure 108 measured mobility interruption times has illustrated.	

	Detailed information about the tests can be found 5G-MOBIX - GR-TR_Agnostic_Test_Results.xlsx file Sheet: TCA-GR-TR-06_InterPLMN_HO_HR TCA-GR-TR-07_InterPLMN_HO_HR D3.7_Appendix-Results_GR-TR.

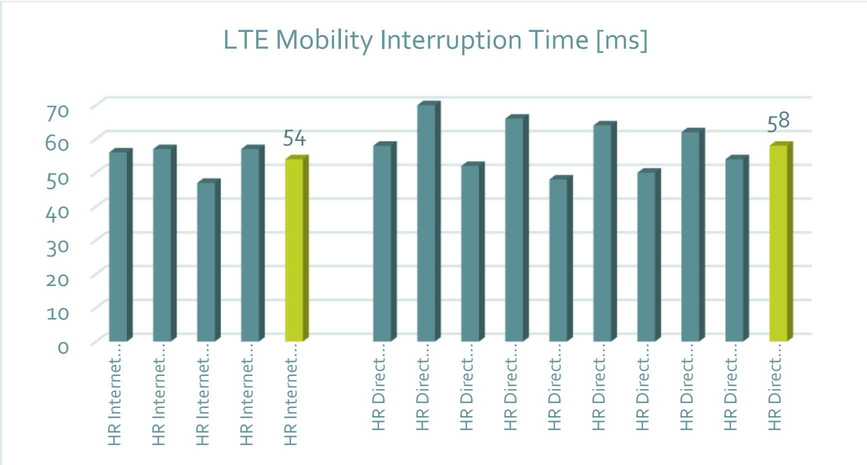

Figure 107: LTE Mobility Interruption time [ms]

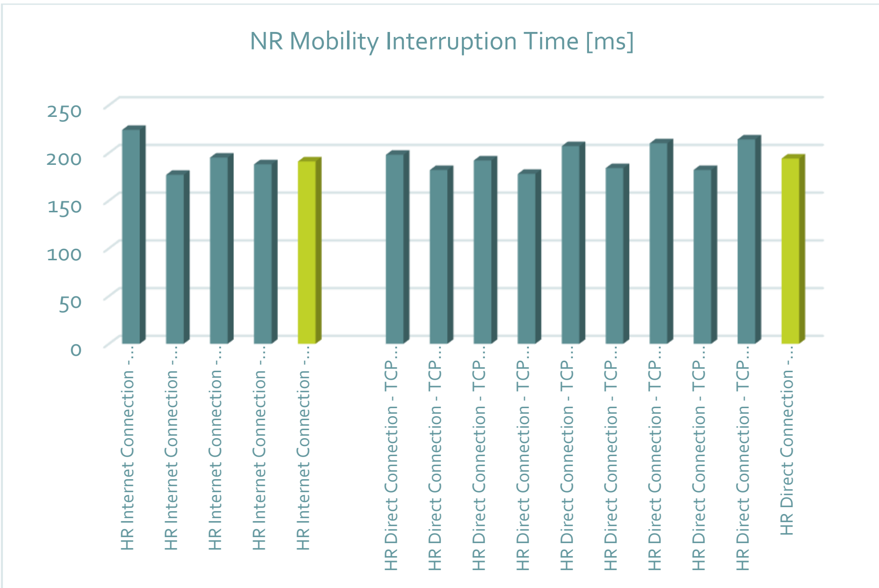

Figure 108: NR Mobility Interruption time [ms]

15. ANNEX 3 – DE MEASUREMENTS & ANALYSIS

16.1 Test setup description

For the agnostic tests in the DE TS, one server located at the TUB data center is used. In this server, a DEKRA agent is deployed and run in server mode. In the UE side, a smartphone with the TACS4-Mobile Android application can be configured to run the different tests against the agent. As there are two different MNOs in the DE TS, the tests have been performed with two different SIM cards, from O2 and DT respectively. The test setup ID for this scheme is DE_Scheme_01.

16.2 KPI_AG1

DL TCP/UDP data throughput of single user with good RF conditions at Ernst-Reuter-Platz round about in DE TS.

Test Location	Straße 17 Juni, Berlin	**Test Case (TC) ID**	KPI_AG1
Test Case (TC) Name	DL TCP/UDP Data Throughput of Single User (stationary use)		
Test Case Purpose	Test throughput under good conditions		
Stationary / Mobility TC	Stationary		
Test environment	Urban		
Test setup ID	DE_Scheme_01		
5G Deployment Option	NSA (option 3x)		
PLMN ID (MCC + MNC)	26201(DT)/26203(O2)		
Test UE Info			
UE Type: Xiaomi Mi 11 *UE category: Smartphone* *UE speed: Stationary*			
Test Variables			
Throughput values can vary depending on the current vehicles and human density. In rush hours, the avenue can be very crowded and values can be much lower			
Expected TC Result			
Maximal TCP DL Throughput from between 250-300 Mbps			
TC Results Report			
Number of repetitions	10		
TC comments	*Results are calculated along the 10 iterations*		
Tools used	*DEKRA TACS4-Mobile Android App*		
TC Logs	*KPI_AG1 - DT TCP DL Stationary.xls* *KPI_AG1 - O2 TCP DL Stationary.xls* *KPI_AG1 - DT UDP DL Stationary.xls* *KPI_AG1 - O2 UDP DL Stationary.xls*		
Test Results (Mbps)	**Iteration #1 - 10**	**Descriptions/Diagrams**	

	TCP DT/O2 – UDP DT/O2	
Avg. DL Throughput	284,46/166,17 – 58,99/44,09	Figure 109: DL TCP Throughput with good conditions - DT SIM Figure 109shows that most values of throughput are as expected for DT and are between 275.and 310 Mbps approx. Figure 110: DL TCP Throughput with good conditions - O2 SIM In the second figure, values for O2 are lower than expected
Min. DL Throughput	32,286/12,45	
Max. DL Throughput	330,218/306,66 - 60,91/49,7	
10th percentile DL Throughput	252,4958/50,59 – 59,58/44,77	
90th percentile DL Throughput	313,199/272,41 – 60,3/45,15	
TC Responsible	*TUB*	
Date	2021-12-16	

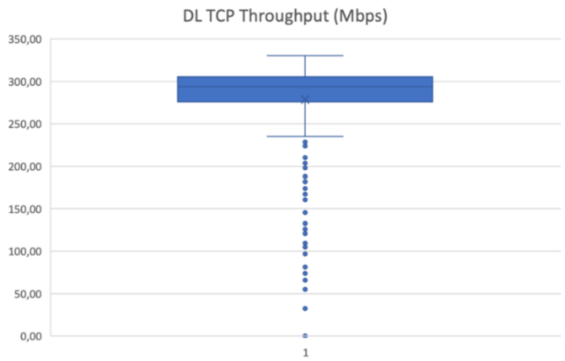

Figure 109: DL TCP Throughput with good conditions - DT SIM

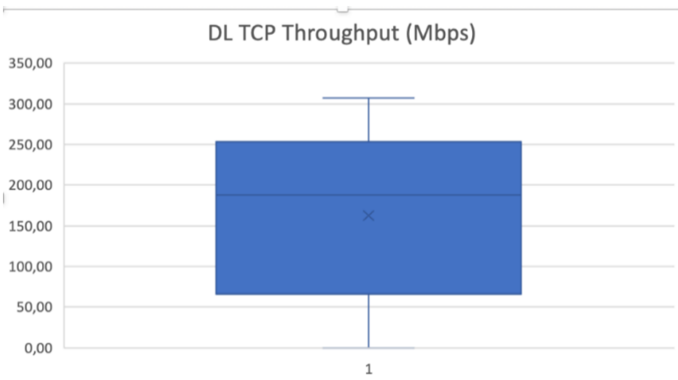

Figure 110: DL TCP Throughput with good conditions - O2 SIM

16.3 KPI_AG2

UL TCP/UDP data throughput of single user with good RF conditions at Ernst-Reuter-Platz round about in DE TS.

Test Location	Straße 17 Juni, Berlin	**Test Case (TC) ID**	KPI_AG2
Test Case (TC) Name	UL TCP/UDP Data Throughput of Single User (stationary use)		
Test Case Purpose	Test throughput under good conditions		
Stationary / Mobility TC	Stationary		
Test environment	Urban		
Test setup ID	DE_Scheme_01		
5G Deployment Option	NSA (option 3x)		
PLMN ID (MCC + MNC)	26201(DT)/26203(O2)		
Test UE Info			
UE Type: Xiaomi Mi 11 *UE category: Smartphone* *UE speed: Stationary*			
Test Variables			
Throughput values can vary depending on the current vehicles and human density. In rush hours, the avenue can be very crowded and values can be much lower			
Expected TC Result			
Maximal TCP UL Throughput from between 50-100 Mbps			
TC Results Report			
Number of repetitions	*10*		
TC comments	*Results are calculated along the 10 iterations*		
Tools used	*DEKRA TACS4-Mobile Android App*		
TC Logs	*KPI_AG2 - DT TCP UL Stationary.xls* *KPI_AG2 - O2 TCP UL Stationary.xls* *KPI_AG2 - DT UDP UL Stationary.xls* *KPI_AG2 - O2 UDP UL Stationary.xls*		
Test Results (Mbps)	**Iteration #1 - 10**	**Descriptions/Diagrams**	

	TCP DT/O2 – UDP DT/O2	
Avg. UL Throughput	47,21/27,17 – 19,64/5,89	Figure 111: UL TCP Throughput with good conditions - DT SIM Figure 112: UL TCP Throughput with good conditions - O2 SIM UL TCP throughput is higher for DT network than for O2.
Min. UL Throughput	34,05/2,04	
Max. UL Throughput	56,54/58,19 - 21,37/6,73	
10th percentile UL Throughput	40,02/13,16 - 19,67/5,86	
90th percentile UL Throughput	53,19/46,15 – 20,23/6,09	
TC Responsible	*TUB*	
Date	2021-12-16	

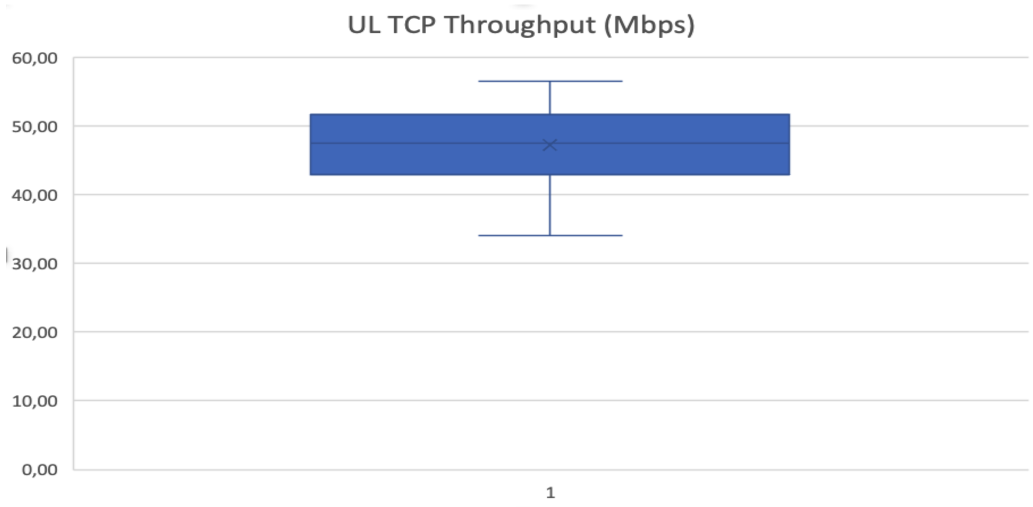

Figure 111: UL TCP Throughput with good conditions - DT SIM

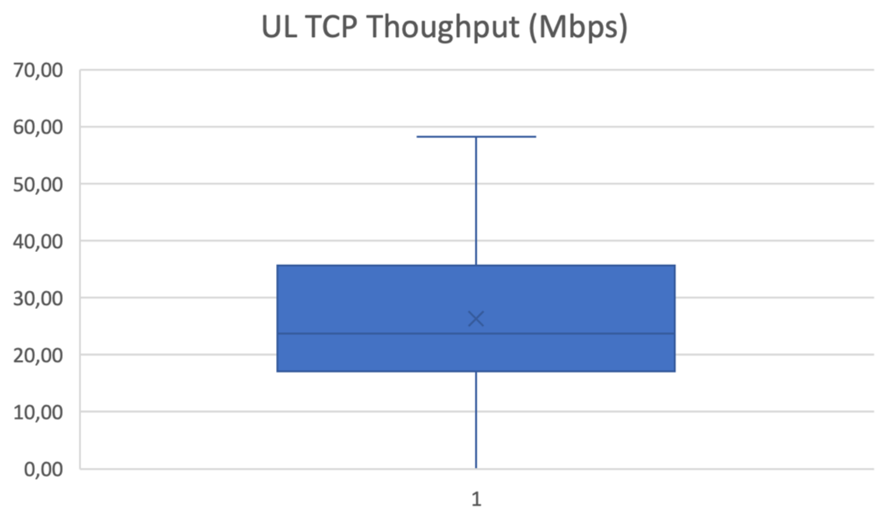

Figure 112: UL TCP Throughput with good conditions - O2 SIM

16.4 KPI_AG3

DL TCP/UDP data throughput for single user with bad RF conditions at a cell edge in DE TS.

Test Location	Straße 17 Juni, Berlin	Test Case (TC) ID	KPI_AG3
Test Case (TC) Name	DL TCP/UDP Data Throughput of Single User (stationary use) in cell edge		
Test Case Purpose	Test throughput under good conditions		
Stationary / Mobility TC	Stationary		
Test environment	Urban		
Test setup ID	DE_Scheme_01		
5G Deployment Option	NSA (option 3x)		
PLMN ID (MCC + MNC)	26201(DT)/26203(O2)		
Test UE Info			
UE Type: Xiaomi Mi 11 *UE category: Smartphone* *UE speed: Stationary*			
Test Variables			
Throughput values can vary depending on the current vehicles and human density. In rush hours, the avenue can be very crowded and values can be much lower			
Expected TC Result			
Maximal TCP Throughput from between 250-300 Mbps			
TC Results Report			
Number of repetitions	*10*		
TC comments	*Results are calculated along the 10 iterations*		
Tools used	*DEKRA TACS4-Mobile Android App*		
TC Logs	*KPI_AG3 - DT TCP DL Cell Edge.xls* *KPI_AG3 - O2 TCP DL Cell Edge.xls* *KPI_AG3 - DT UDP DL Cell Edge.xls* *KPI_AG3 - O2 UDP DL Cell Edge.xls*		
Test Results (Mbps)	Iteration #1 - 10 TCP DT/O2 – UDP DT/O2	Descriptions/Diagrams	
Avg. DL Throughput	144,74/43,30 – 19,62/14,01	In Figure 113 DL TCP Throughput in cell edge - DT SIM and Figure 114 DL TCP Throughput in cell edge - O2 SIM, throughput values at the cell edge (lowest RSRQ available at the DE TS) are presented. Again, the UL TCP throughput is higher for DT network than for O2, as the figures show.	
Min. DL Throughput	3,22/3,17		
Max. DL Throughput	312,71/101,05 – 21,39/17,14		
10th percentile DL Throughput	49,90/18,09 – 19,78/12,59		
90th percentile DL Throughput	239,06/70,12 – 20,11/15,05		
TC Responsible	*TUB*		

Date	2021-12-21

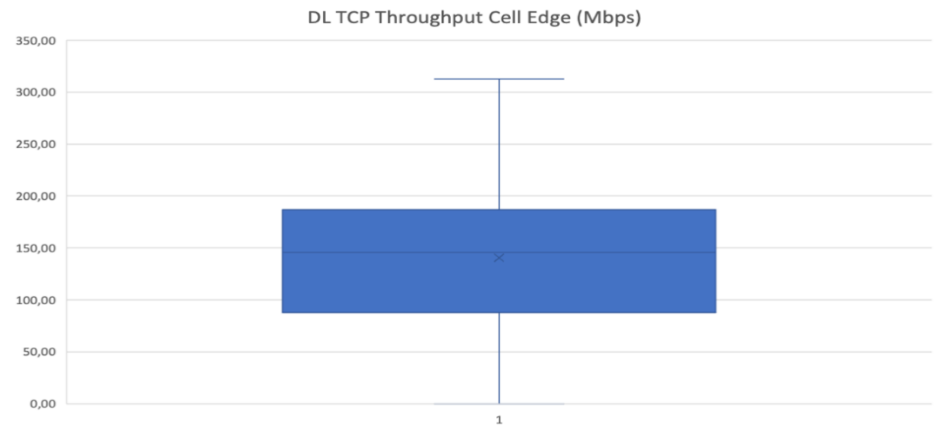

Figure 113: DL TCP Throughput in cell edge - DT SIM

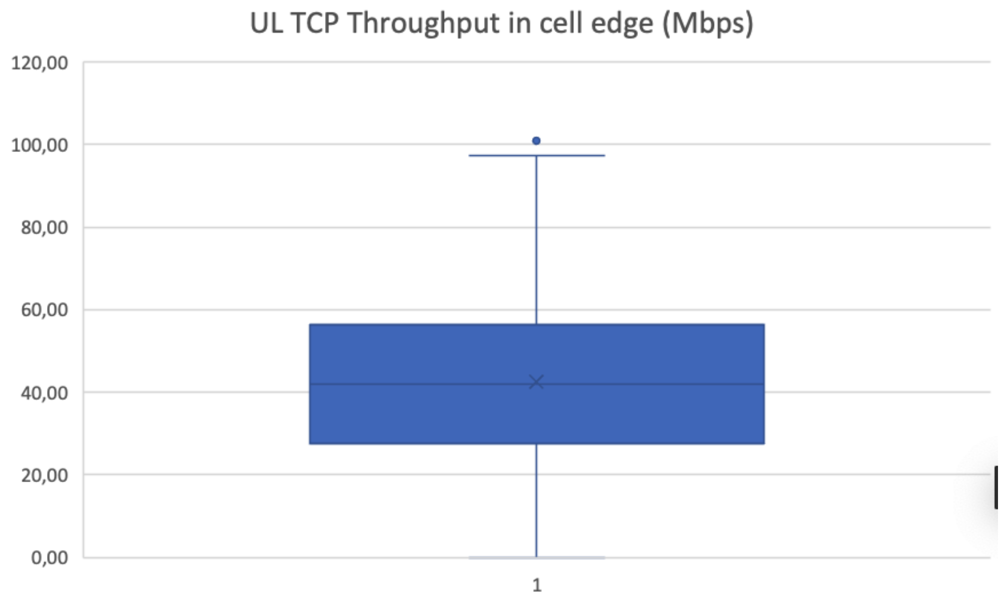

Figure 114: DL TCP Throughput in cell edge - O2 SIM

More information on DE TS annex section is provided in the the following document: [5G-MOBIX - D3.7 - appendices - v0.1 - DE.docx (sharepoint.com)]

16. ANNEX 4 – FI MEASUREMENTS & ANALYSIS

The FI TS has leveraged 5G networks commercial mobile networks from two different operators (Elisa and Telia) with coverage in the Otaniemi area for additional trial activities (for both the remote driving and extended sensors user stories. Each of the two networks operates in NSA mode utilising the 3.5 GHz TDD band for 5G NR (each with 130 MHz bandwidth allocation) and LTE anchors in the 2.6 GHz band. The coverage maps for these networks obtained from drive tests carried out on the designated test route prior to the trials is shown in Figure 115 (Network A = Telia and Network B = Elisa). It is noted that the two networks and 5G NR coverage footprint that is many cases complementary. This coverage pattern provides for interesting scenarios for multi-PLMN operations, whereby, a vehicle (OBU) on trajectory of the test route may interchangeably the any of the two networks at different points depending on quality of the connection.

Figure 115: Drive test coverage results (RSRP) for the two networks utilized in the specific trials in FI-TS

The contrast in the achievable performance between the networks case also be observed in the TCP and UDP throughput results obtained from the drive tests in the same test route as shown Figure 116. The results consider both the NR-only case, as well as the ENDC (E-UTRA NR Dual Connectivity) case for devices capable of aggregating LTE and NR carriers.

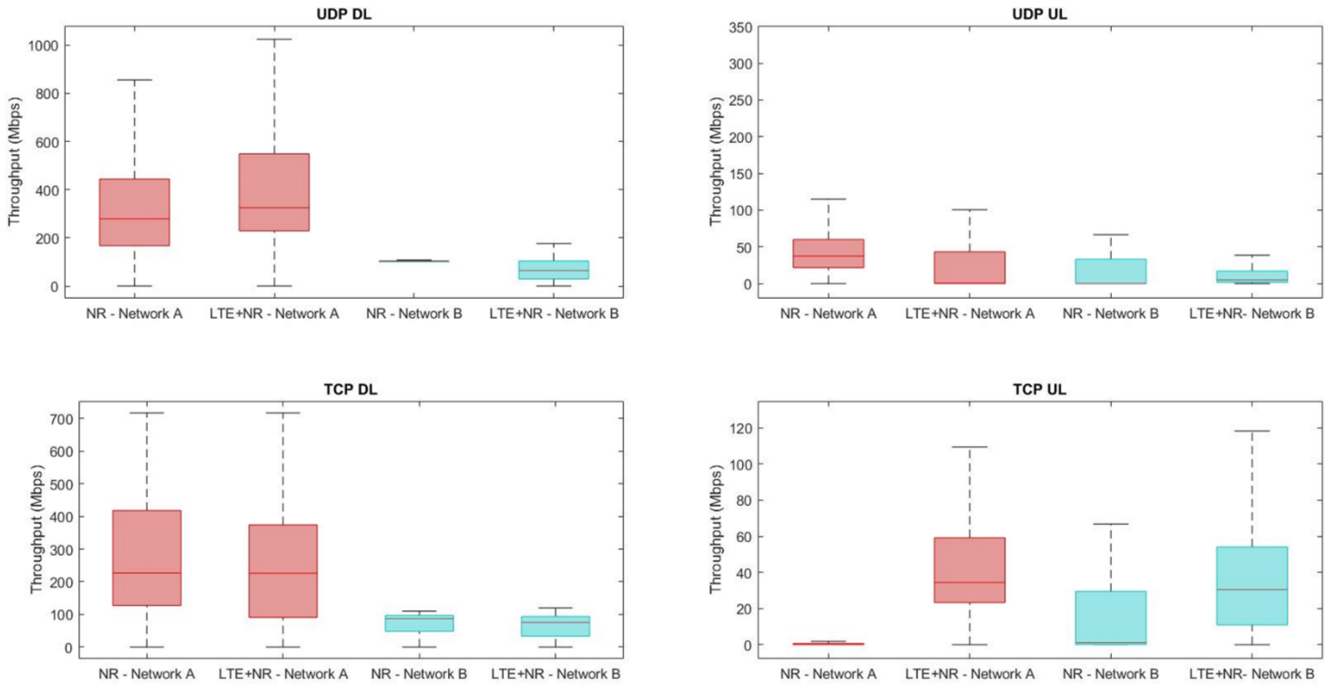

Figure 116: Drive test throughput results (TCP and UDP) for the two networks utilized in the specific trials in FI-TS

More information on FI TS annex section is provided in the following directory:
[5G-MOBIX - D3.7_Appendix-Results_FI - (sharepoint.com)]

17. ANNEX 5 – FR MEASUREMENTS & ANALYSIS

Whole report for ES-PT CBC/France: Network TC Result FR.xlsx

This report presents all the results at ES-PT CBC and France. The current document presents the results of the use-case agnostic test cases that are to tackle the following cross border issues and considered solutions.

Table 61: Use-case agnostic test cases for FR measurements

Cross border issue	Cross border issue solution
XBI_5: Session & Service continuity	CS_4 Multi-modem / multi-SIM connectivity - Passive Mode
XBI_5: Session & Service continuity	CS_5 Multi-modem / multi-SIM connectivity – Link Aggregation
XBI_1: NSA roaming interruption	CS_1: S1 handover with S10 interface using an NSA network

Performances of 5G NSA networks (cmWave and mmWave) have been assessed with public sub 6GHz and private mmWave networks at FR TS. Figure 117 shown the latency for data upload in a TCP communication in one trial. Here, the latency is on average 23ms with peak up to 75ms.

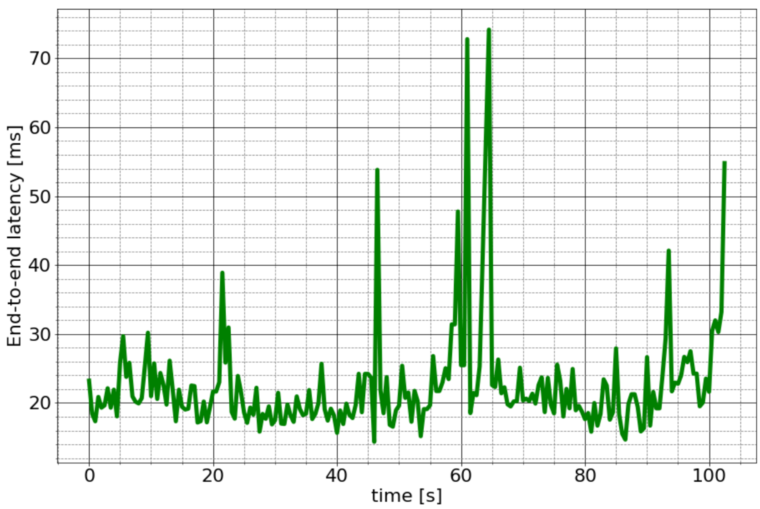

Figure 117: Latency measure in 5G sub 6GHz NSA network during a TCP UL communication

Complementary, Figure 118 highlights distribution of the maximum throughput in both upload and download for the two tested networks configurations. It shows the public 5G NSA network in sub 6GHz currently offer more throughput than private 5G NSA network in mmWave in both UL and DL. Additionally, UL has higher throughput the DL with both configurations. The gaps observed with 5G network in mmWave may be explained by the fact that this network is still under test and to be finely tuned. Thus, further validation will be continued.

Although performances are not maximal, these initial tests have shown that both networks are up and can be used for more intensive testing.

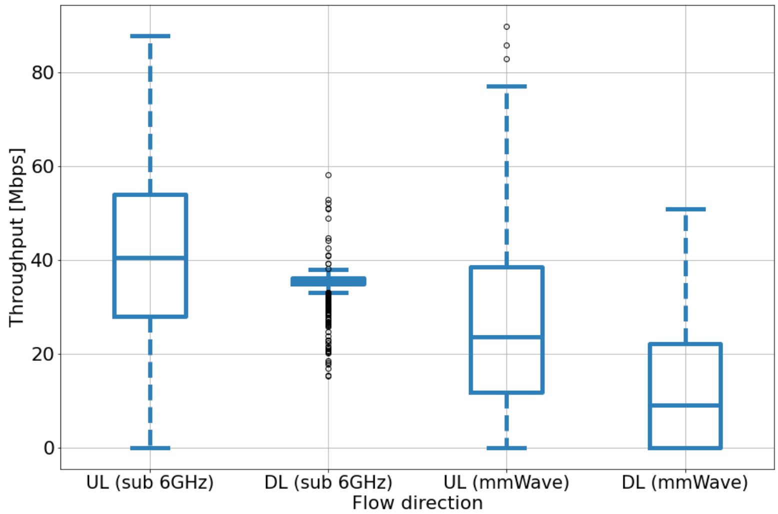

Figure 118: Throughput distribution for different flow direction with sub 6GHz and mmWave 5G NSA networks

Multi-SIM connectivity has been tested by FR TS as a solution to ensure service continuity at a cross-border corridor. This solurion has been tested with two public NSA networks (Orange and Bouygues). Note that the coverages of the two networks highly overlaps (the gNBs are installed in at the same location). Figure 119 and Figure 120 show the packet loss rate in passive mode and with link aggregation. First, packet lost with passive mode takes an average value of 0.4% in passive mode. Second packet loss rate with link aggregation at a low speed provide excellent results, 0% packet loss and 20ms delay. Therefore, this approach has been considered as a valid solution when networks conditions are good, i.e. both networks are overlapping.

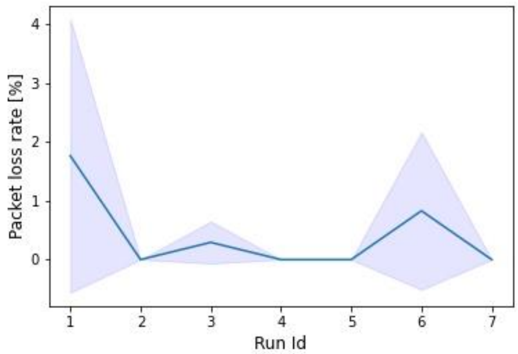

Figure 119: Average packet loss for test iterations of multi-SIM connectivity in passive mode

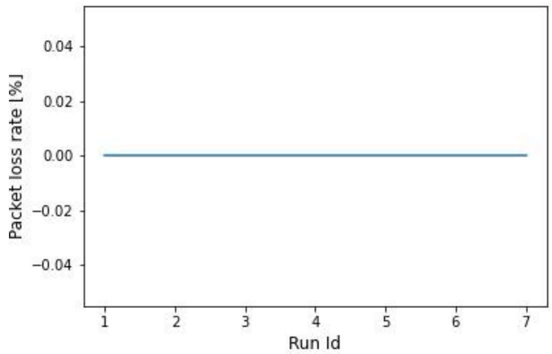

Figure 120: Average packet loss for test iterations of multi-SIM connectivity with link aggregation

Predictive QoS has been developed and demonstrated on top of 5G networks by FR TS to ensure continuity of QoS to applications. Relying on the collection of network and access indicators while assessing the performance of TCP communications, a complete training dataset has been built, as illustrated by the different features of Figure 121.

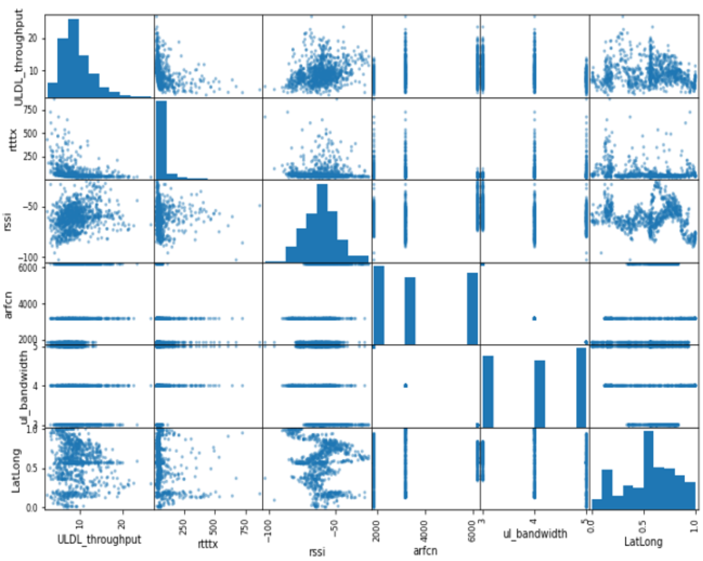

Figure 121: Features collected for training QoS prediction models

Then, a model has been learning and implemented in a server to monitor online the conditions of a given user equipment and adapt its transmission parameters, i.e. the data rate. As shown in Figure 122, different services of the V2X communication stack may require different data rate, hence, based on the predictive

QoS model, the user equipment can dynamically adapt to the network conditions, especially when they are degrading.

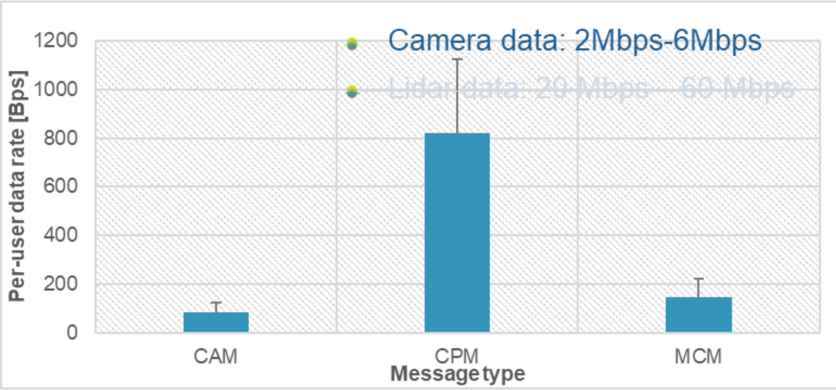

Figure 122: Expected data rate for different V2X Services

All results of the test cases conducted in FR TS are available in the test case report excel file.

18. ANNEX 6 – NL MEASUREMENTS & ANALYSIS

Test Setup Description

TNO network - Below figures show the two different setups used during (agnostic) tests.

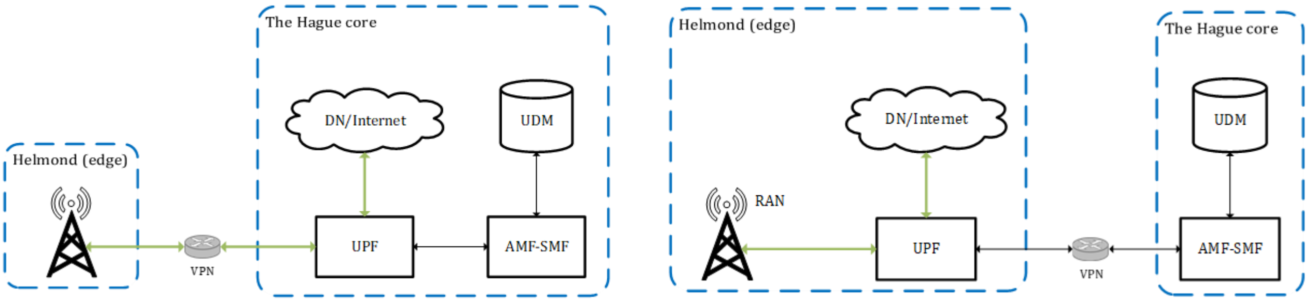

Figure 123: NL TS Core Routing (Left) and LBO Routing (Right) Setup (Edge-Core Network)

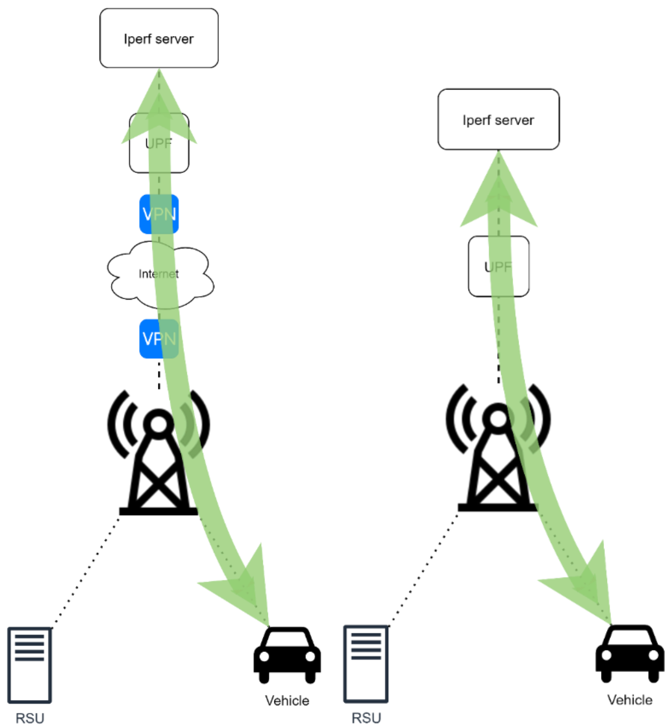

Figure 124: NL TS Core Routing (Left), NL LBO Routing (Right) Setup (Vehicle-Iperf Server)

KPI_AG1 DL (TNO)

Test Location	Neervoortse Dreef		Test Case (TC) ID	KPI_AG1
Test Case (TC) Name	DL Data Throughput of Single User (Mbps) - stationary / Central			
Test Case Purpose	Measure the maximum, minimum and average TCP DL throughput under the best RF conditions in over 1 minute.			
Stationary / Mobility TC	Stationary			
Test setup ID	**Error! Reference source not found.**			
5G Deployment Option	SA (option 2)			
PLMN ID (MCC + MNC)	20495			
Test UE Info				
UE Type: Fibocom (FM150-AE) *UE category: Modem* *UE SW version: 89605.1000.00.02.01.02*				
TC Results Report				
Number of repetitions	2			
TC comments	*TCP protocol. DL throughput. Best RF conditions. 1 minute long.*			
Tools used	*iperf*			
Test Results	Iteration #1 (TCP)	Iteration #2 (UDP)		
Max throughput (Mbps)	571	513		
Min throughput (Mbps)	112	388		
Average throughput (Mbps)	443	437		
Average Spectral Efficiency (b/s/Hz)	4,4	4,4		
TC Responsible	*TNO*			
Date	*18/02/2021*			

KPI_AG1 DL (KPN)

Test Location	Helmond automotive campus	Test Case (TC) ID	KPI_AG1
Test Case (TC) Name	Peak DL TCP/UDP Data Throughput of Single User (stationary use)		
Test Case Purpose	Test throughput under good conditions		
Stationary / Mobility TC	stationary		
Test environment	Helmond automotive campus		
Test setup ID	20220425_01		
5G Deployment Option	SA (option 2)		
PLMN ID (MCC + MNC)	20469		
Test UE Info			
UE Type: M2 type quectel modemcard RM510Q *UE category* *UE SW version RM510QGLAAR11A02M4G_BETA_20220104G* *UE speed Max. downlink 4.5Gbps / 2.9Gbps uplink*			
Test Variables			
Indicate any condition that could have an impact on the test result and any possible deviation compared to the test case description.			
Expected TC Result			
TC Results Report			

Number of repetitions	8			
TC comments	*Add here any main observations*			
Tools used	*iperf3*			
TC Logs	*20220420_01_tcp_downlink_good_coverage.log*			
Test Results	Iteration #1	Iteration #2	Iteration #3	Descriptions/Diagrams
Throughput received (mbps)	607	277	440	
<Metric2 measured>				
<Average Metric measured>	441			
TC Responsible	*KPN*			
Date	*20220420*			

KPI_AG5 DL (TNO)

Test Location	A270/N270		Test Case (TC) ID	KPI_AG5
Test Case (TC) Name	DL Data Throughput of Single User (Mbps) - Mobile			
Test Case Purpose	Measure the maximum, minimum and average TCP DL throughput in the range from excellent RF conditions value to bad RF conditions value in over 1 minute.			
Stationary / Mobility TC	Mobility			
Test setup ID	**Error! Reference source not found.**			
5G Deployment Option	SA (option 2)			
PLMN ID (MCC + MNC)	20495			
Test UE Info				
UE Type: Fibocom (FM150-AE) *UE category: Modem* *UE SW version: 89605.1000.00.02.01.02*				
TC Results Report				
Number of repetitions	1			
Tools used	*Iperf*			
TC Logs	*https://erticobe.sharepoint.com/:x:/r/sites/5G-MOBIX/Workplan/WP3%20Development,%20integration%20and%20rollout/T3.1%20Corridor%20roll-out%20coordination/D3.7/Appendix-Results/D3.7_Appendix-Results_NL/d3.7/TNO/accessaggregation_3101_20220419T150119_down_100mhz.csv?d=wcb127e788f3148ccbbfef5e208422680&csf=1&web=1&e=kxBQG5*			
Test Results	Iteration #1			
Max throughput (Mbps)	238			
Min throughput (Mbps)	2			
Average throughput (Mbps)	95			
10th Percentile throughput (Mbps)	3,1			
90th Percentile throughput (Mbps)	171,9			
Average Spectral Efficiency (b/s/Hz)	0,95			
TC Responsible	*TNO*			
Date	*19/04/2022*			

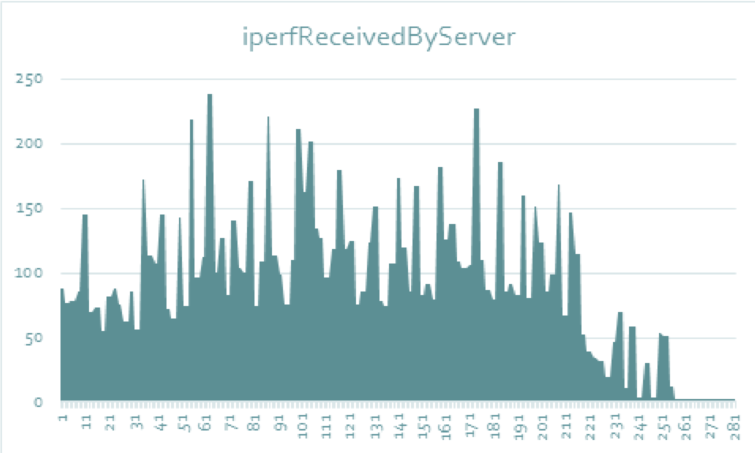

Figure 125: NL TS KPI_AG5 (TNO) DL Throughput Measurement

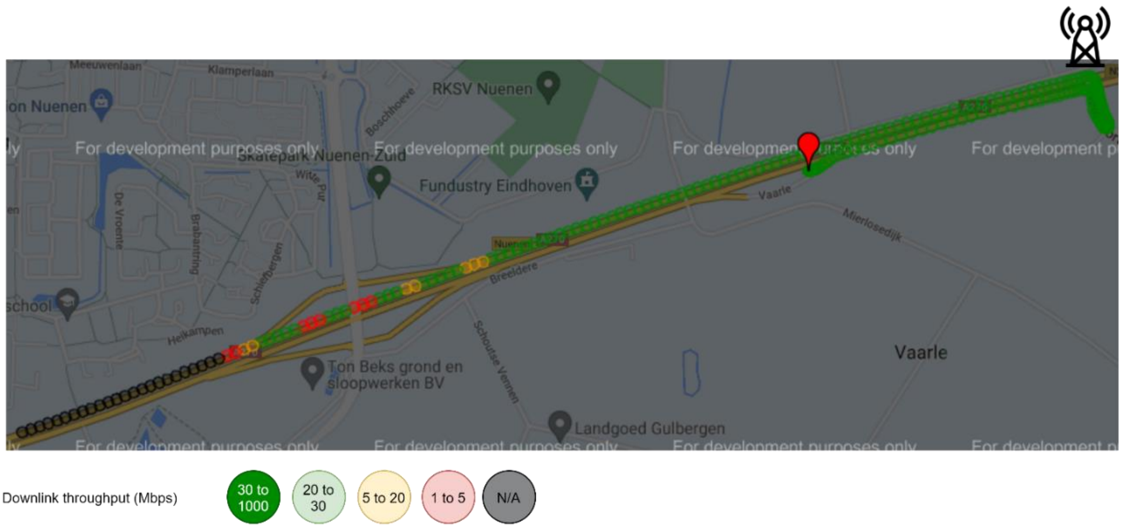

Figure 126: NL TS KPI_AG5 (TNO) DL Throughput Measurement Site

KPI_AG5 DL (KPN)

Test Location	Automotive Campus	Test Case (TC) ID	KPI_AG5
Test Case (TC) Name	DL Data Throughput of Single User (Mbps) - Mobile		
Test Case Purpose	Measure the maximum, minimum and average TCP DL throughput in the range from excellent RF conditions value to bad RF conditions value in over 1 minute.		
Stationary / Mobility TC	Mobility		
Test setup ID	20220425_01		
5G Deployment Option	SA (option 2)		
PLMN ID (MCC + MNC)	20469		
Test UE Info			

UE Type: M2 type quectel modemcard RM510Q *UE category* *UE SW version RM510QGLAAR11A02M4G_BETA_20220104G* *UE speed Max. downlink 4.5Gbps / 2.9Gbps uplink*			
TC Results Report			
Number of repetitions	1		
Tools used	*Iperf*		
TC Logs	20220511_down_link_drivetest.csv		
Test Results	**Iteration #1**		
Max throughput (Mbps)	299		
Min throughput (Mbps)	83		
Average throughput (Mbps)	192		
10th Percentile throughput (Mbps)	90		
90th Percentile throughput (Mbps)	256		
Average Spectral Efficiency (b/s/Hz)	1,91		
TC Responsible	*KPN*		
Date	*11/05/2022*		

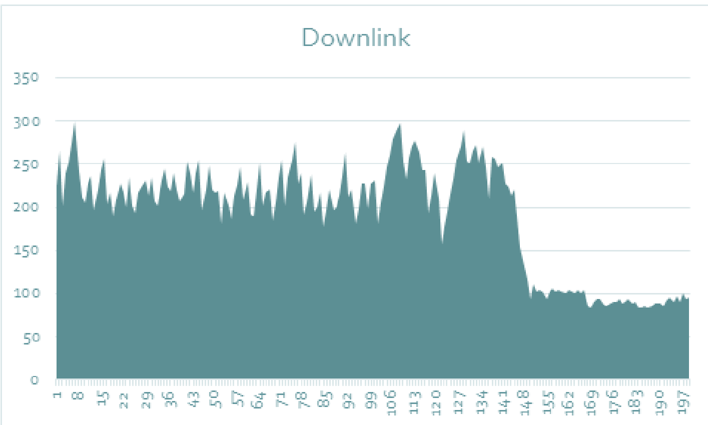

Figure 127: NL TS KPI_AG5 (KPN) DL Throughput Measurement

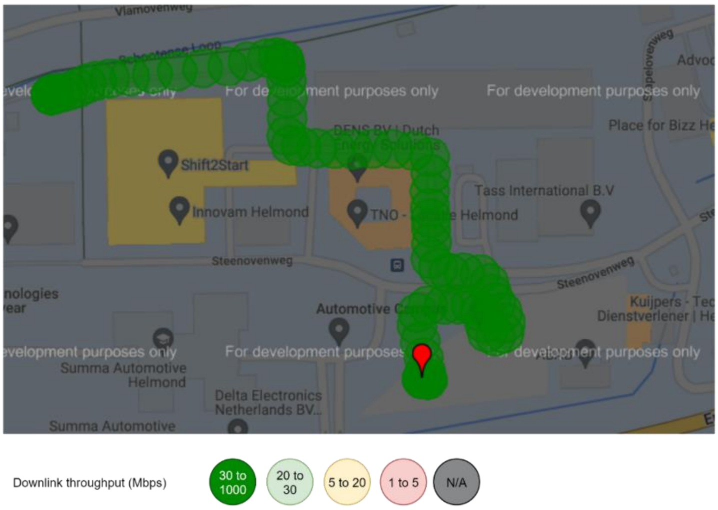

Figure 128: NL TS KPI_AG5 (KPN) DL Throughput Measurement

TU/e mm-wave measurements

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 129 shows the deployment and its location on TUE campus, including the antenna locations, beam sizes and field of view with beamsteering. The radiation pattern of the individual antennas is also shown, alongside a map of the resulting EVM 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 %

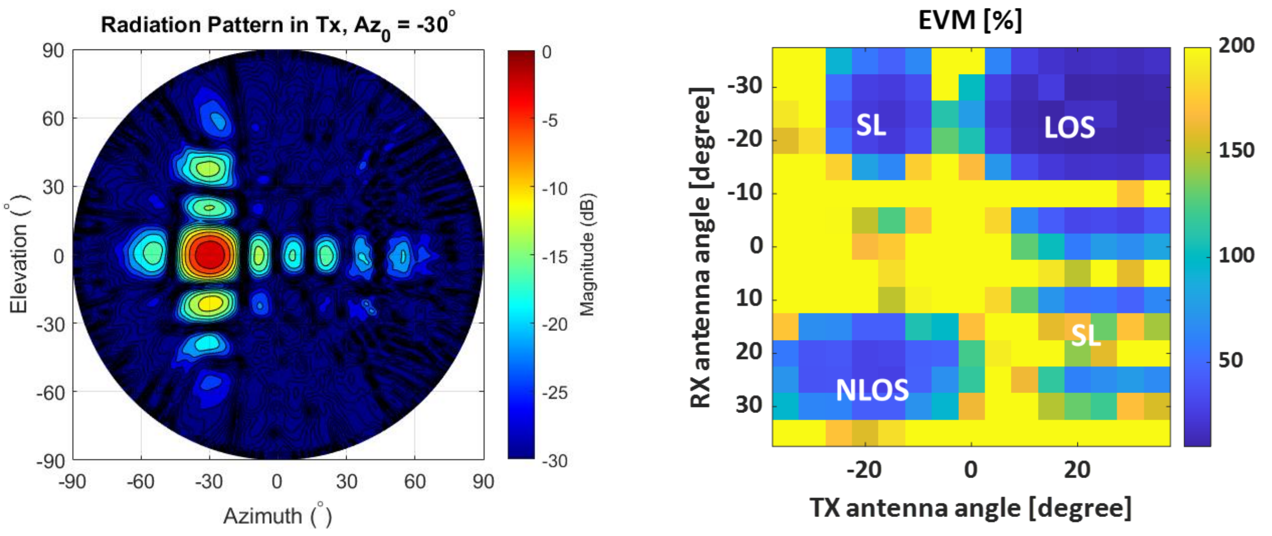

Figure 129: Mm-wave measurements at TU/e. Top: measurement equipment and overview map showing antenna directions and field of view with beamforming as well as setup parameters and main results. Bottom: Antenna radiation pattern and measured EVM across Tx and Rx sc

More information on NL TS annex section is provided in the following link:

[5G-MOBIX - D3.7 -appendices - v0.2 - NL.docx (sharepoint.com)]

19. ANNEX 7 – CN MEASUREMENTS & ANALYSIS

In CN TS, we leveraged 5G networks commercial mobile networks from two different operators (China Mobile and China Unicom) with coverage in the Eastern of SDIA area for additional trial activities. This solution provides session redundancy for multi-PLMN operations; thus, a vehicle (OBU) on trajectory of the test route may select the high-priority connection or utilize multiple connections in the same session between the two networks at different points depending on quality of the connection. The maps of results throughput for these networks obtained from drive tests carried out on the designated test route are shown in Figure 130.

Test Location	CN TS	Test Case (TC) ID	TCA-CN-09
TC Name	DL performance of multi-SIM connections in 5G network		
Test Case Purpose	Performance analysis when multi-SIM connections are used		
Stationary / Mobility TC	Mobility		
5G Deployment Option	SA		
Test environment	Eastern of Shandong academy sciences, Jinan		
CS	CS5: Multi-modem / multi-SIM connectivity - Link Aggregation		
Test UE Info			
UE Type: MH5000-871 UE module : 5G NR/LTE-FDD/LTE-TDD/HSPA+ UE speed : 25 km/h			
Test Variables			
Test done in UDP at central coverage area of the 5G gNB in DL			
Expected TC Result			
Validation of 5G Connectivity and assess throughput and end-to-end latency.			
TC Results Report			
Repetitions	3 runs		
Tools used	iperf		
Test Results	Iteration #1	Iteration #2	Iteration #3
Aver. Tput (Mbps)	305.435	325.895	321.425
Peak Tput (Mbps)	532.032	543.351	482.004
Packet loss rate	0.823	0.806	0.832
End to end latency	25	21	22
TC Responsible	SDIA		
Date	2022/5/25-2022/6/2		

General comments and conclusions	Multi-SIM solution with link aggregation mode is not affecting to user plane throughput level and significant fluctuation of end-to-end latency, see Figure 130.

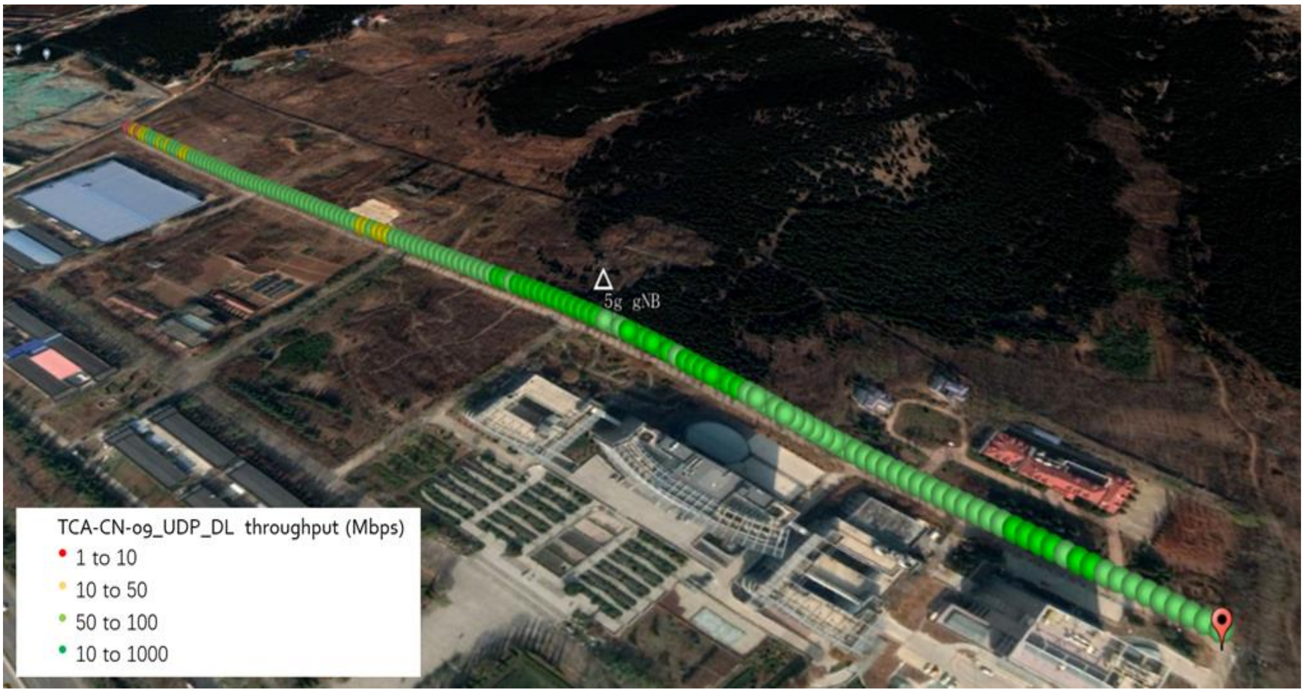

Figure 130: Throughput measure 5G SA network during a UDP DL communication

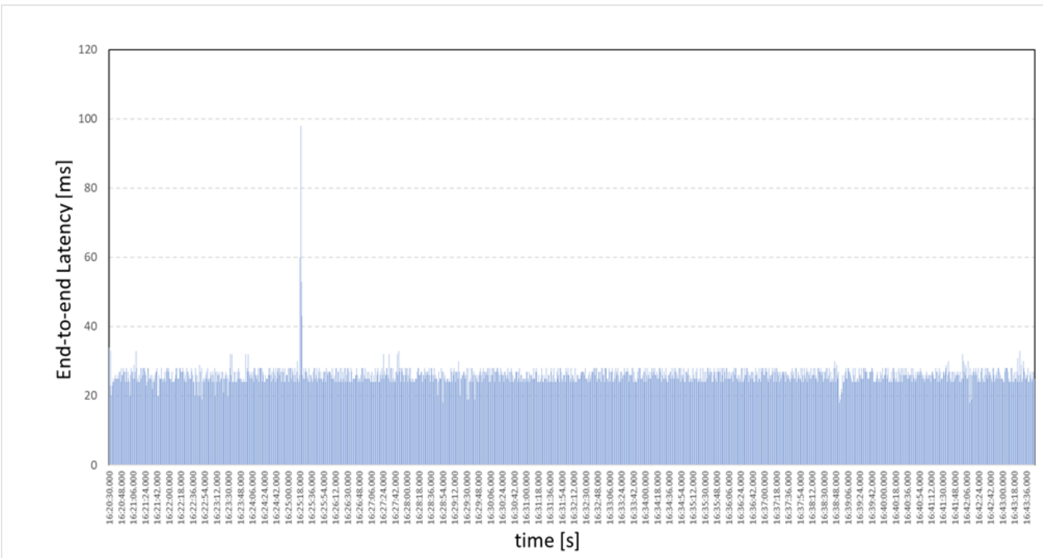

Figure 131: Latency measure in 5G SA network during a UDP DL communication

Test Location	CN TS	Test Case (TC) ID	TCA-CN-11
TC Name	DL performance of multi-SIM connections in 5G network		
Test Case Purpose	Performance analysis when multi-SIM connections are used		
Stationary / Mobility TC	Mobility		
5G Deployment Option	SA		
Test environment	Eastern of Shandong academy sciences, Jinan		
CS	CS5: Multi-modem / multi-SIM connectivity - Passive Mode		
Test UE Info			
UE Type: MH5000-871 UE module : 5G NR/LTE-FDD/LTE-TDD/HSPA+ UE speed : 25 km/h			
Test Variables			
Test done in TCP at central coverage area of the 5G gNB in DL			
Expected TC Result			
Validation of 5G Connectivity and assess throughput and end-to-end latency.			
TC Results Report			
Repetitions	3 runs		
Tools used	iperf		
Test Results	Iteration #1	Iteration #2	Iteration #3
Aver. Tput (Mbps)	230.354	265.902	268.322
Peak Tput (Mbps)	439.913	395.301	432.521
Packet loss rate	0.991	0.923	0.952
User Plane Interruption time (ms)	40	53	44
End to end latency	29	31	29
TC Responsible	SDIA		
Date	2022/5/25-2022/6/2		
General comments and conclusions	Multi-SIM solution with the passive mode is affecting to user plane throughput level and slight fluctuation of end-to-end latency, see Figure 132.		

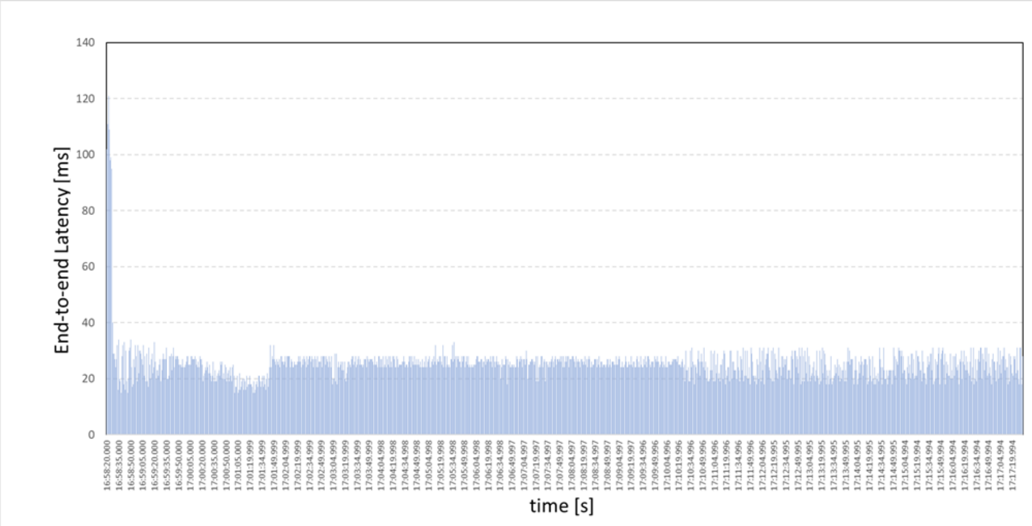

Figure 132: Latency measure in 5G SA network during a TCP DL communication

More information on CN TS annex section is provided in the following document: [5G-MOBIX - D3.7 - appendices - v0.1 - CN.docx (sharepoint.com)]()