WHITE PAPER from 5G-Blueprint, 5GMED, and 5G-ROUTES

Enabling Seamless Connected Automated Mobility in cross-border Scenarios through 5G Technology

05/06/2025

Abstract

This White Paper presents insights from the three ICT-53 projects 5G-Bluepring, 5GMED, and 5G-Routes related to providing seamless service continuity (with the shortest disruption) for automotive services through 5G Standalone (SA) networks, particularly in cross-border scenarios. The three projects successfully performed demos showing the feasibility of providing uninterrupted services in three cross-border corridor areas: Belgium-Netherland, France-Spain, and Estonia-Latvia. To provide acceptable interruption times when crossing country borders, different technologies at core and radio access network levels were developed and evaluated. In particular, the 5GMED project deployed and evaluated Local Break-out (LBO) roaming that enables the use of Mobile Edge Computing (MEC) in an efficient way. In addition, enabling technologies such as radio access network sharing, neutral host, and MEC federation and orchestration were also evaluated. The technologies and results presented in this white paper shows how 5G SA networks enables the deployment of Connected and Automated Mobility (CAM) services can be efficiently deployed in cross-border scenarios and unblock all their capabilities. The white paper also discusses the challenges, and the lessons learned while deploying 5G technologies for CAM services in cross-border scenarios.

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1. Introduction

Four projects were funded by the European Commission's H2020-ICT-53-2020 call under the topic 5G for Connected and Automated Mobility (CAM) with focus on cross-borders scenarios. Three of these projects had cross-border use cases (UCs) deployed on highways with connected vehicles: 5G-Blueprint [1], 5GMED [2], and 5G-ROUTES [3]. The main common objective of the three projects was to ensure seamless service continuity and high-quality communications for CAM services across international borders in challenging cross-border scenarios.

Although each project used different approaches, one of the main challenges of the three projects is to maintain uninterrupted services' connectivity, especially crossing international borders, where vehicles' User Equipment (UE) undergoes roaming procedure to move from one Public Land Mobile Network (PLMN) to another. In addition to the change of Mobile Network Operators (MNOs), crossing borders will implicitly imply change of telco-vendors, network configuration, telco-related regulations (e.g., used frequencies, frame configuration, etc.), and Mobile Edge Computing (MEC) operators.

In this context, 5G-Blueprint, 5GMED, and 5G-ROUTES deployed 5G Standalone (SA) networks in different borders to provide connectivity to a plethora of CAM use cases. This white paper presents a summary of the UCs trialled by each project, and their requirements, the 5G network solutions deployed, the key performance evaluation results obtained from trials, and lessons learned. Before starting the technical details, the three projects are briefly described below.

5G-Blueprint: The objective of 5G-Blueprint was to design and validate the advanced 5G network architecture for tele-operation of vehicles and vessels in cross-border scenarios, while designing and validating business and governance models for tele-operated transport. The key aspects that 5G-Blueprint covered to achieve the abovementioned objective are: i) 5G enablers for reliable and uninterrupted teleoperation, focusing on ultra-low latency, reliable connectivity, and high bandwidth requirements; ii) teleoperated transport on roadways and waterways as an ultimate tool for solving the challenge of manpower shortage and decreased efficiency in the transport and logistics sector; and iii) testing and validation of technical and operational preconditions for achieving the full potential of 5G in transport and logistics, such as implementing real-life UCs that guarantee safe and responsible teleoperated transport. To create the blueprint for operational pan-European deployment of 5G-enhanced cross-border teleoperated transport, 5G-Blueprint developed several UCs such as Automated Vessel Transport and Teleoperation-based Platooning of vehicles and trucks, which were tested and validated in the cross-border area. Although the project has tested and validated the developed technologies in two national pilot sites (Antwerp and Vlissingen sites situated in port environments, in Belgium and The Netherlands, respectively) and one international/cross-border pilot site (BE-NL cross-border area in Zelzate), this whitepaper focuses only on the results obtained in the cross-border site.

5GMED: The objective of the 5GMED project was to demonstrate advanced CAM services for the automotive sector (in addition to railway, not discussed in this white paper) along the Mediterranean cross-border corridor between Figueres (Spain) and Perpignan (France). These services were enabled by a multi-stakeholder compute and 5G network infrastructure deployed by MNOs, neutral hosts, and road and rail operators, based on 5G Standalone (SA). Key aspects of the 5GMED project outlined in this document include: i) cross-border 5G network architecture and roaming optimization, with a focus on different types of roaming and their implications; ii) strategies implemented to ensure service continuity and reduce interruption times during inter-PLMN transitions; iii) evaluation of network performance in terms of latency, throughput and interruption time in cross-border scenarios; and iv) implementation of MEC federation and network orchestration for efficient resource management between different MNOs. In this context, three automotive UCs were developed by 5GMED and trialled along the mediterranean cross-border corridor: high-speed tele-operated driving, road infrastructure digitalization, and follow-me infotainment.

5G-ROUTES: The 5G-ROUTES project has two ecosystems terrestrial and maritime, with the aim to provide uninterrupted connectivity and service continuity on both roadways at international borders and national waterways. In this whitepaper, the focus will be on the terrestrial ecosystem and provide insights to the 5G-specific solutions for CAM UCs trialled at the border crossings between Estonia and Latvia. This is achieved by developing, setting up, and configuring 5G-specific and integrated technologies such as precise positioning and end-to-end network slicing. For the CAM services, a set of innovative Technological Enablers (TEs) have been developed and integrated into the CAM services platform which is co-located to the 5G core network. The CAM services platform is a cloud-native platform running on top of the 5G mobile network, whose aim is to handle the lifecycle management of virtualised CAM services. The terrestrial ecosystem consists of following use cases: i) see-through platooning; ii) sharing perception and road hazard; and iii) Infotainment, with 360° immersive multi-user gaming on the go, as well as 3D real-time virtual collaboration on the move.

This reminder of this whitepaper is organised as follows. Section 2 presents the requirements of the use cases. Section 3 describes the implemented 5G network solutions to provide seamless services in cross-border scenarios. Section 4 discusses the obtained performance results of the 5G SA networks and implemented solutions. Section 5 briefly describes the cross-border MEC federation and orchestration solutions. Section 6 presents the lessons learnt and recommendations.

2. Use cases' requirements

CAM services and use cases are diverse and have different network requirements. Depending on the application, the most challenging requirement can be bandwidth, latency, interruption time, reliability, or jitter. Since the three projects involved different use cases and were evaluated in different environments, their network requirements also differ, as outlined below.

2.1. 5G-Blueprint use cases

Due to its relevance for testing and validation of automotive services in the cross-border area between Belgium and The Netherlands, here we tackle one of the 5G-Blueprint use cases, i.e., Teleoperation-based Platooning of vehicles and trucks. This use case considered a combination of teleoperated and human-driven vehicles in a platoon, whereas the lead vehicle could be either teleoperated or human-driven.

The main requirements are listed as follows: 1) uplink throughput of at least 5 Mbps per sensor/camera installed on the remotely controlled vehicle, 2) maximum end-to-end latency of 35 ms for the remote control, and 100 ms for telemetry traffic, and 3) service interruption time not higher than 150 ms for both uplink camera traffic (from the teleoperated vehicle to the remote control centre) and remote control (from the control centre to the teleoperated vehicle), to ensure seamless operation over the country borders.

2.2. 5GMED use cases

Three automotive use cases were evaluated in the 5GMED project: high-speed tele-operated driving use case, road infrastructure digitalization, and follow-me infotainment.

In the high-speed tele-operated driving, the main requirements were: 1) the throughput of the video transmission in the uplink, which should be above 2 Mbps to enable remote driving at a speed of 50 km/h; 2) the latency between the remote station and the tele-operated vehicle in the downlink, which should be lower than 100 ms to avoid late commands to the vehicle; and 3) the mobility interruption time, which should be lower than 100 ms to ensure service continuity.

For the road infrastructure digitalisation use case, the main requirements were: 1) latency, which should be lower than 200 ms so that ITS messages arrive on time; and 2) interruption time, which should be lower than 100 ms.

Finally, the main requirements of the follow-me infotainment use case were: 1) round-trip latency, which should between 80 and 100 ms depending on the service; 2) throughput, which should be between 1 Mbps and 100 Mbps depending on the service; and 3) interruption time, which should be below 100 ms in the most constrained services.

As a summary, and to guarantee a seamless mobility for the three use cases, the following requirements were set on the network: 1) round trip latency between the UE and the User Plane Function (UPF) below 35 ms; 2) throughput above 100 Mbps; and 3) interruption time below 100 ms.

2.3. 5G-ROUTES use cases

There are several requirements in the 5G-ROUTES project, each of which depends on the use case or the application. For the See-Through Platooning use case, which utilizes video transmission and V2X messages transmitted between the vehicles, the throughput (user experienced data rate), the target value depends on the type of data traffic in the use case. The target value is the highest for video transmission and amounts to 15 Mbps. Whereas for the V2X message transmission, the messages transmitted are smaller, in the order of 100-1000 bytes transmitted 1-20 times per second; therefore, the data rate is in the order of 1 Mbps. As for Latency (communication end-to-end latency), the target latency for video transmission is 50 ms for the median and 100 ms for the 95% percentile. For the V2X message transmission, 20 ms is set as target value for the median and 50 ms for the 95% percentile. As for the localization, localization accuracy is critical for autonomous overtaking manoeuvre and use cases such as the sensor information sharing for cooperative situation awareness. In this case, a localization accuracy of about 10 cm is needed. The target service interruption time when crossing borders is 1 second, while the CAM service (video proxy) instantiation target time is 30 seconds. As for the Sharing perception and road hazard use case, the throughput is between 4-24 kbps. The target latency is 20 ms. The target accuracy of roadwork vehicle location is below 50 cm.

The 360° Immersive Multiuser Gaming on the Go use case, the target throughput is 5 Mbps. The latency is 60 ms. The service interruption time is 5 s. The CAM service instantiation time is 30 s. The remaining KPIs are similar to the See-Through Platooning use case.

The 3D Real-Time Virtual Collaboration on the Move use case, the target throughput is 10 Mbps. The one-way latency is 1 s. The service interruption time is 5 s. The CAM service instantiation time is 30 s. The localization accuracy is not critical for this use case.

3. Cross-border 5G network architecture and seamless roaming

Based on the requirements of the three ICT-53 projects (5G-Blueprint, 5GMED, and 5G-ROUTES) as well as the requirements of the ICT-18 projects [4], existing deployments of commercial mobile networks, including 5G, cannot maintain seamless service continuity in cross-border scenarios and result in service interruption times that range from tens of seconds to a few minutes during roaming. Fortunately, the average interruption time can be reduced to 120 ms using the seamless roaming solutions provided by the ICT-18 projects (5G Non-SA) and around 100 ms with the solutions provided by ICT-53 (5G SA) projects: 5G-Blueprint, 5GMED, and 5G-ROUTES.

3.1. Main concepts

In this section we present the main concepts and techniques available in the standards, which were implemented in the ICT-53 projects to decrease the interruption time in cross-border scenarios.

In general, two types of roaming are possible [5]:

1. **Home-routed roaming (HRR) with support of visited Public Land Mobile Network (vPLMN)**. In the HRR scenario, represented in Figure 1, the data from a UE connected to a visited network is routed to the Data Network via the home network. With HRR in default mode, the roaming process is carried out with new registration of the UE and typically performs an interruption time up to 2 min when a user equipment moves from one country to another. This type of roaming was deployed by the three projects.
2. **LBO roaming**. In LBO roaming, the data traffic stays within the visited network and, therefore, does not involve the SMF and UPF of the home network. LBO roaming is expected to show a reduced latency in the user data plane with respect to HRR. The LBO roaming was deployed only in 5GMED.

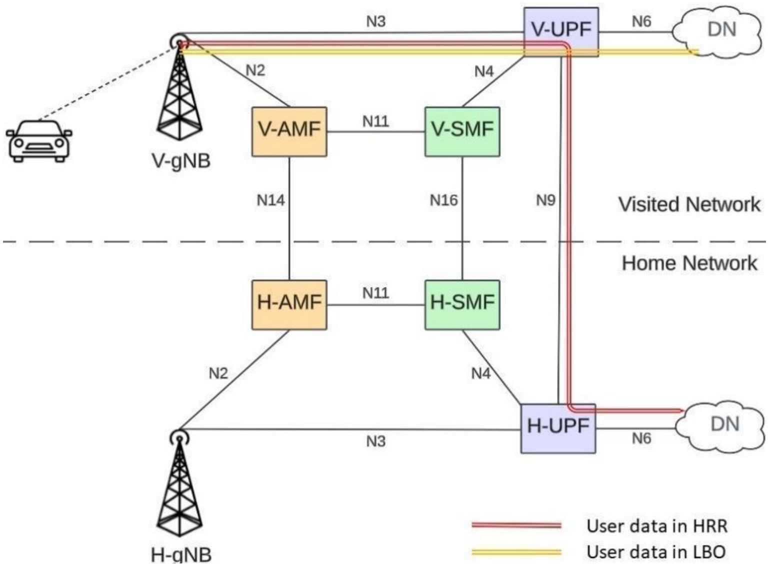

Figure 1 User plane data flow when either Home-Routed Roaming (in red) or Local Break-Out roaming (in orange) is used.

When a UE crosses the borders between two countries, different procedures can be applied to switch from one PLMN to another.

- Network reselection[1]: Legacy procedure.
- Idle mode mobility: UE roaming with Access and Mobility Management Function (AMF) relocation using N14 interface.
- Inter-PLMN handover.

It should be noted that the two last options are the options used to decrease the interruption time in cross-border scenarios.

[1] The name "Network reselection" was chosen as the baseline solution similar to the white paper of ICT-18 projects [2] and is considered as the baseline solution.

In **network reselection**, the UE (modem, router, or smartphone) at the border of two countries will remain connected to its home PLMN until the connection is lost (most probably due to very weak signal). Then, the UE will start a procedure of selecting a new PLMN, which will include scanning the radio frequencies and attempting to connect to available PLMN. Therefore, this procedure is normally very long and can take from several seconds to several minutes.

In **idle mode mobility**, the two AMFs (home AMF and visited AMF) are connected through the N14 interface. The N14 interface allows the two AMFs exchange the UE context information. The AMF in the visited-PLMN (vPLMN) can fetch the UE context from the source AMF, thus reducing the registration/authentication time. The N14 interface is a must to implement the handover between different PLMNs, so that the source (controlling) network gets information from the UE about potential target 5G cell for handover in the vPLMN. In addition, the two PLMNs are configured as equivalent PLMNs (e-PLMN) to reduce the scanning time in the radio network. This will allow a faster roaming in idle mode. The control plane messages exchanged during roaming procedure using N14 interface is depicted in Figure 2.

In **inter-PLMN handover**, the 5G cells at the border were configured as neighbour cells in addition to the activation of e-PLMN and N14 interface between the vPLMN and hPLMN, which will allow a UE in connected mode to have a service continuity as it is in normal intra-PLMN handover. The roaming process, represented in Figure 1, is transformed into an N2-based handover from radio point of view. The UE reports to its network the measured signal power of the in the v-PLMN neighbour cell, and when the conditions are met, the source network will initiate the handover procedure.

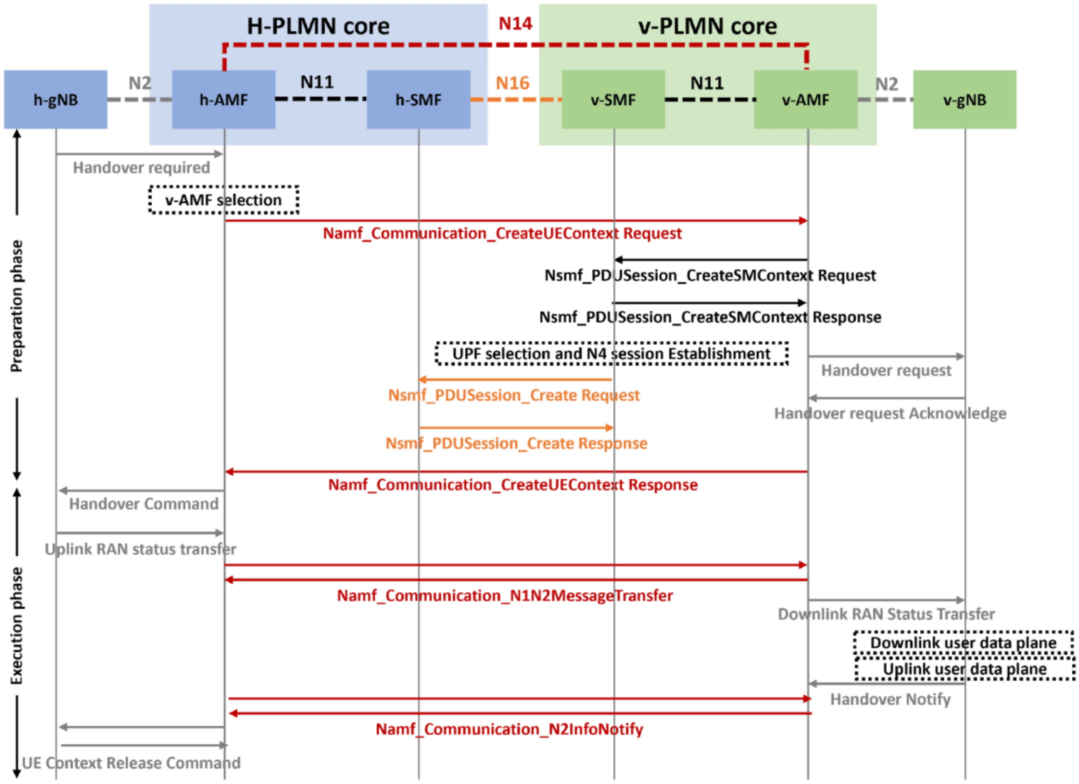

Figure 2 Roaming procedure when using the N14 interface [6].

3.2. Detailed implementation

The inter-PLMN handover has been deployed in the three ICT-53 projects (as shown in Figure 3). The deployed architecture includes the enhancements both in the core network (N14 interface) and in the radio network (Neighbour cell relation)

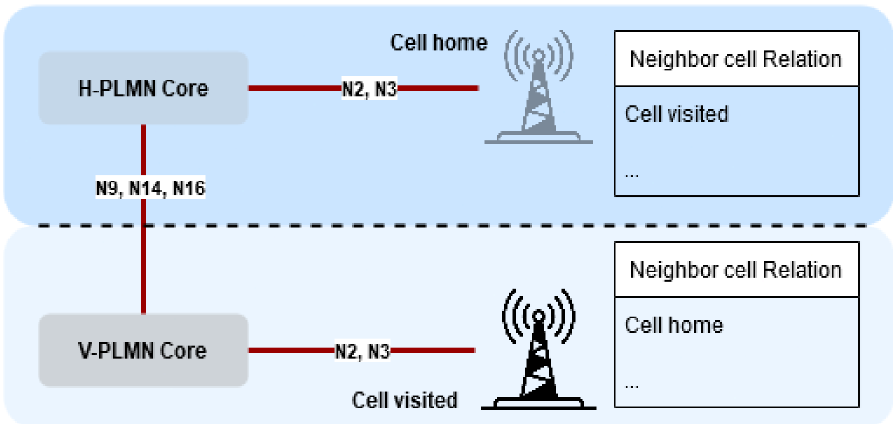

Figure 3 The inter-PLMN handover deployed by the ICT-53 projects.

However, two different approaches were considered by the ICT-53 projects to deploy the inter-PLMN handover: (1) two 5G standalone networks, developed in 5G-Blueprint and 5GMED; and (2) multi-operator core network, developed in 5G-ROUTES.

Two 5G standalone networks

To explain the advanced roaming mechanism developed and tested in the **5G-Blueprint and 5GMED** projects, we first present the simplified 5G network architecture, which captures the high-level configuration on the radio and core network sides (Figure 4). This architecture overview sheds light on essential 5G Core functions interacting with each other to enable seamless roaming (inter-PLMN handover) with negligible interruption time.

The roaming methodology deployed in 5G-Blueprint and 5GMED is the following:

- Deployment of two instances of 5G Core (same vendor), connected with subsequent radios from different operators (and different vendors).
- gNobeB handover when signal strength drops below the predefined threshold.
- Home-routed roaming and N2 handover over the N14 interface.

In 5G-Blueprint, the radio part of the network consists of two gNBs deployed by two different telco operators (Telenet in Belgium, and KPN in the Netherlands). In 5GMED, six gNBs were deployed in Spain (Vodafone and Cellnex) and six gNBs were deployed in France in the corridor between Figueres and Perpignan. In both cases, two different RAN vendors were used in the two sides of the border.

Following the service-based architecture, the implementation of the 5G Core is flexible and scalable, and two instances of the same 5G Core were deployed, one 5G Core in each network. The 5G Core used in 5G-Blueprint is a specialized core based on the open-source solution Open5GS. 5GMED deployed the Raemis 5G Core of Druid.

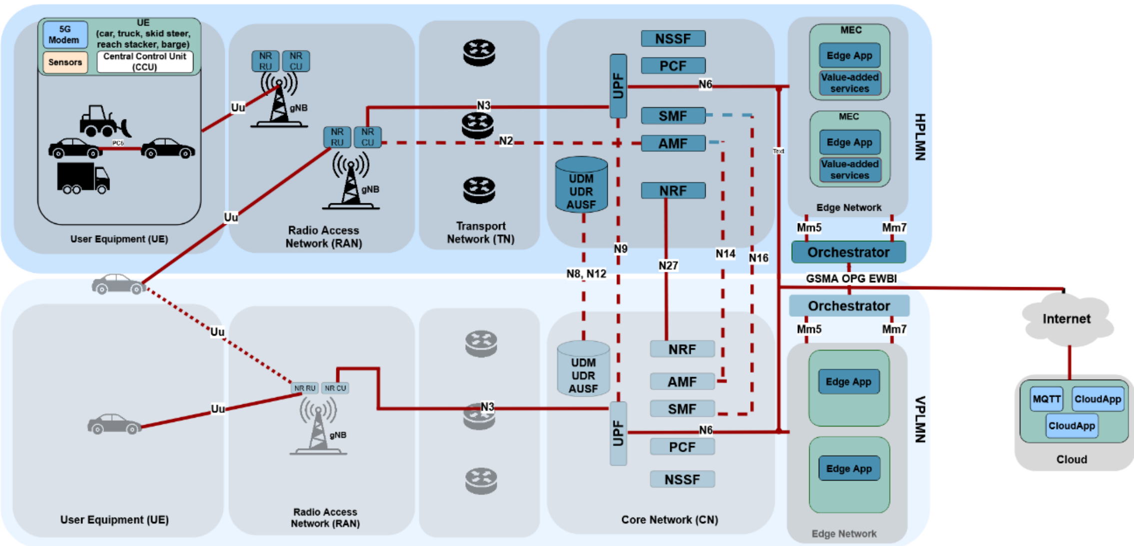

Figure 4 Simplified 5G network architecture used in 5G-Blueprint and 5GMED.

To decrease the interruption time, the signalling between the two 5G Core instances is handled over the N14 interface using HRR mode, as described in Section 4.1. For instance, when a vehicle (car or truck) is crossing the border, peering 5G Core instances interact to transfer the UE state and maintain its session to minimize the interruption time. This whole process results in fewer messages exchanged between 5G Core functions, which ultimately decreases the overall interruption time, as peering SMF instances do not exchange data during the handover process itself (inter-PLMN SMF interaction would introduce more significant delays as compared to intra-PLMN procedures) [6][7]. After the UE connects to the new cell, the vPLMN receives a Handover confirm message, and the uplink is established properly. Due to the above-described procedure (vPLMN AMF informs hPLMN AMF about the handover completion, which further informs hPLMN SMF about the session and interface modification), the N9 interface is now used for transferring data traffic, making it possible to continue the service operation, e.g., transferring video and sensor feeds over the uplink from the teleoperated vehicle to the remote-control center.

In addition, LBO roaming with N14 interface was also deployed in 5GMED. As the Session and Service Continuity (SSC) mode 3 was not supported by the used UEs and enabled LBO roaming in connected mode without re-establishing a new PDU session, the Source Network Address Translation (SNAT) was set in both UPFs for N6 traffic. This allows LBO UE traffic egressing on the N6 interface to be SNATed to the target networks N6 subnet. For example, a UE that has performed inter-PLMN handover from Spain to French 5G network is technically assigned an IP address from the Spanish SMF (e.g., 10.17.201.X), however, if this UE's traffic were to egress the French networks d-UPF N6 (10.17.207.0/24) then this traffic would not be routable. So, instead, SNAT has been configured in the French d-UPF N6 so traffic egressing on the N6 gets SNATed to a UE-IP pool on the 10.17.207.0/24 subnet.

Multi-operator core network

The 5G-ROUTES project utilizes a **multi-operator core network deployment**, featuring a shared RAN networks with two core networks (one being used in the 5G-ROUTES, while other used by Telia Estonia for their commercial 5G NSA traffic), as illustrated in

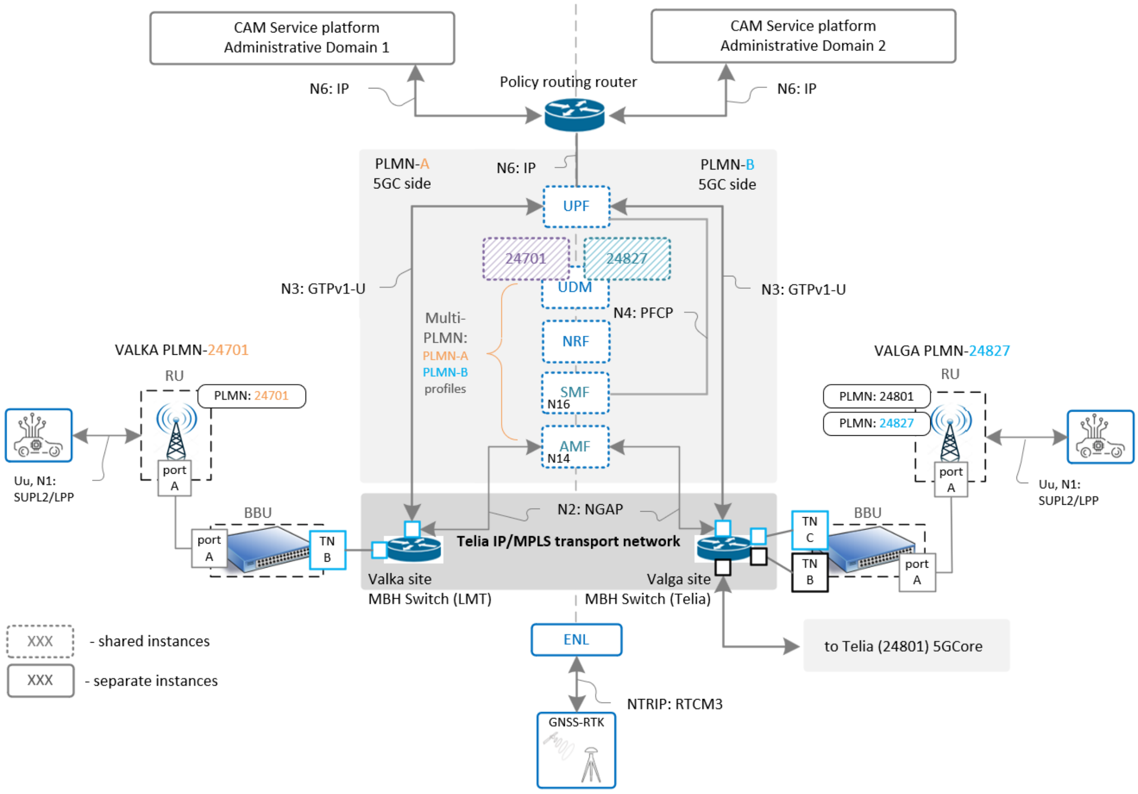

Figure 5. An Ericsson's 5G Core is installed in Tallinn (at Tallinn University of Technology), Estonia (approximately 230 km from the trial site). The roaming solutions implemented include home-routed and LBO roaming while inter-PLMN handover was used for the radio handover. At the Valga-Valka trial site, two 5G RANs were deployed, one in each country. The setup features two base stations with distinct PLMNs, each connected to the UPF via different transport networks. Additionally, the co-located CAM services platform comprises a suite of virtualized applications, technological enablers, an ETSI OSM orchestrator, and a Kubernetes (K8) cluster, integrated over the N6 interface with a customized networking solution.

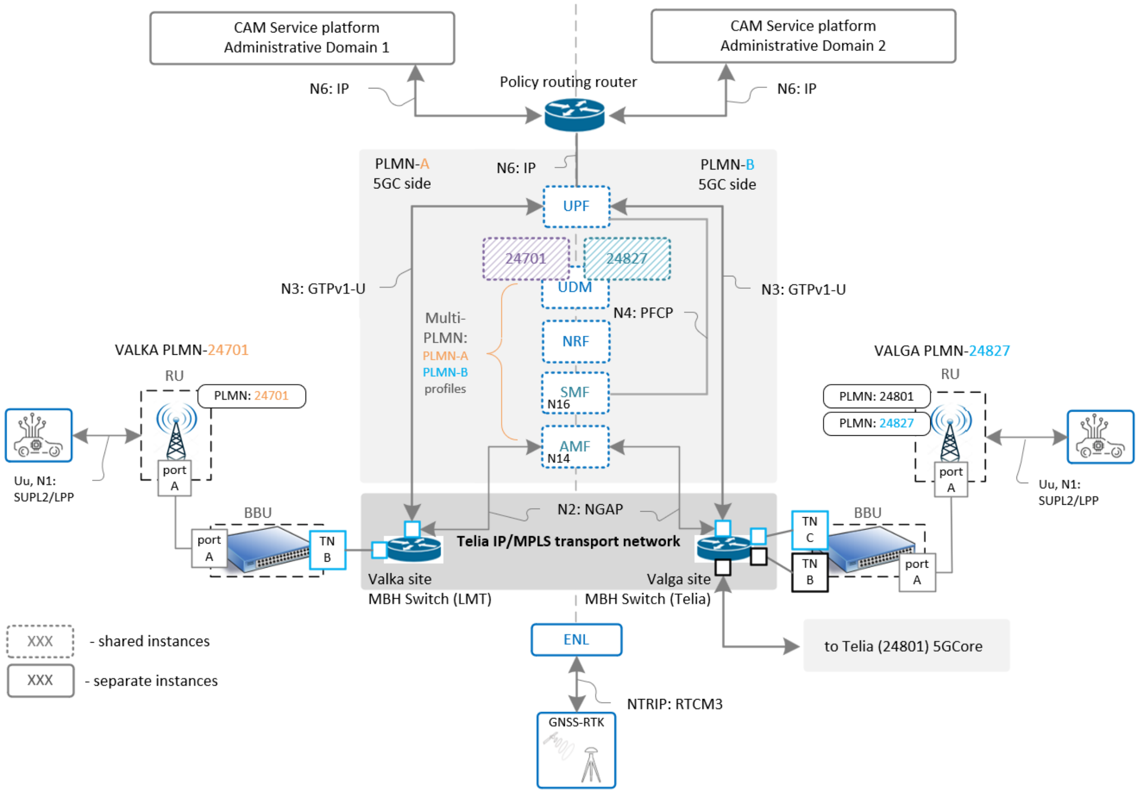

Figure 5 Terrestrial network deployment architecture representing 5G Core, Transport and RAN network with dedicated interfaced for the Shared 5G core and shared 5G RAN in 5G-ROUTES.

5G-ROUTES technical solution is cloud-based Small Size Target Solution (SSTS) 5G Core network, with support for the Multiple PLMN feature. This feature allows the creation of up to 12 different virtual mobile networks in one 5G SA Core network. This feature enabled roaming between different PLMN networks, which technically means national (local) roaming. The country codes of different mobile networks are used, which mimics international roaming. The required PLMN codes need to be defined in both AMF and SMF. Roaming is implemented in such a way that mobility occurs seamlessly from one PLMN network to another through handover between the radio network and the AMF.

In the radio networks, the handover can be triggered under different conditions called events. In 5G-ROUTES, both A3 events and A5 events are used. In addition, a hysteresis of -3dB and a delta parameter, which was set to -1dB, to trigger handover were implemented.

To enable handover between two different PLMNs to reduce service interruption during roaming, it is necessary to use the N14 interface between the AMFs. However, since in 5G-ROUTES there is one physical 5G Core (i.e., the single AMF resource for both PLMNs), therefore, there is no need to separately implement the N14 interface and the N14 functionality is already implemented in its Multiple PLMN feature.

In addition, a Mobility Restriction List IE in the Registration and Mobility Management for the AMF can contain a serving PLMN and equivalent PLMNs that are used to steer the UE into selecting a target PLMN during the handover procedures.

On the SIM card, the code of the second roaming PLMN was added to the parameters EFHPLMNwACT (Home PLMN selector with Access Technology), EFOPLMNwACT (Operator Controlled PLMN selector with Access Technology) and EFPLMNwACT (User Controlled PLMN selector with Access Technology) in addition to the home network. In addition, the code of the second roaming PLMN EFEHPLMN (Equivalent HPLMN) was defined as the equivalent home network. With such settings, roaming between PLMNs of virtual networks is ensured.

An illustration of the multi-PLMN solution of 5G- ROUTES is shown in Figure 6, where two PLMNS (PLMN A, and PLMN B) are deployed. It can be observed that the multi-PLMN is flexible in the sense that network functions such as AMF, SMF, and NRF can host multiple PLMNs. These PLMNs can be deployed in network functions at various locations in the network, or in just one location. The RAN can also support one or more PLMNs. Additionally, Figure 6 illustrates the operation of the inter-PLMN handover, where a UE served by PLMN A must perform a handover once it moves from its coverage area to the coverage area of PLMN B.

The multi-PLMN does not cause any performance degradation, nor does it have any impact on the network's performance metrics, such as throughput, signalling capacity, CPU load, or memory consumption.

The handover procedures are based on standardized N2 and Xn type handover- For example, the Xn type handover used in the 5G-ROUTES project, works as follows:

The UE is constantly sending measurement reports to its serving gNB ("source gNB", i.e. PLMN A Figure 6). Based on the configurations, once the source gNB detects that the UE needs to be handed over to another gNB ("target gNB", i.e. PLMN B Figure 6), it makes a handover decision. Then, the source gNB sends a handover request to the target gNB and once it is accepted, the handover execution commences (more details can be found in[5]).

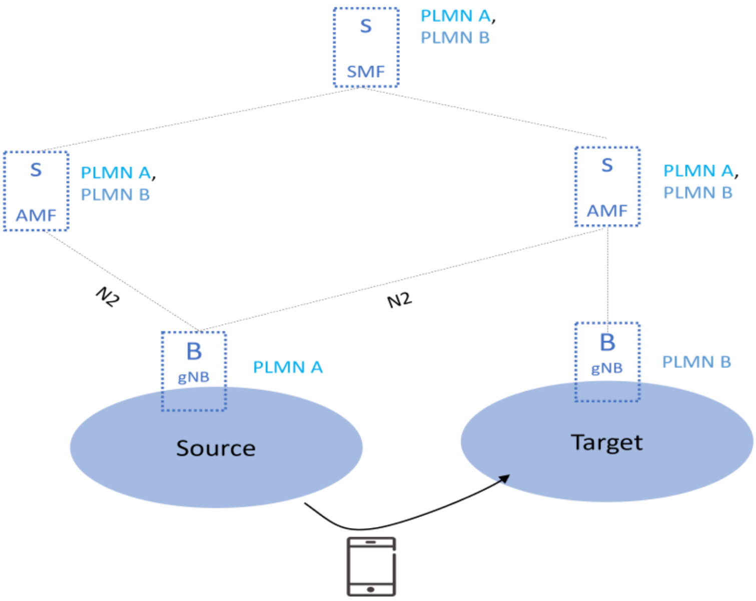

Figure 6 Multi-PLMN solution in 5G-Routes.

In Table 1, we present for the three projects the roaming type (HRR or LBO), the core optimization techniques, and the RAN optimization techniques that were used to reduce the interruption time in cross-border scenarios.

Table 1 Summary of used technologies to reduce inter-PLMN interruption time.

	Roaming type	Core optimization	RAN optimization
5G-Blueprint	HRR	N14	Neighbour cell relation
5GMED	HRR & LBO	N14	//
5G-Routes	HRR	Multi-operator core network	//

3.3. RAN sharing and neutral host

The interaction between the network infrastructure layers is made through specific cross-border interfaces for 5G roaming and the implementation of a Neutral Host Infrastructure concept. The Neutral Host concept was implemented in 5GMED and 5G-ROUTES. An example of implementation of the Neutral Host Infrastructure concept in 5GMED is that the French 5G network infrastructure is designed for Multi Operator Core Network (MOCN) Radio Access Network (RAN) sharing, which is a cost-effective solution for MNOs. As for the 5G-ROUTES, the Estonian 5G network is designed as MOCN for the project, in which the RAN of commercial network is shared with TalTech. The MOCN scheme allows sharing the baseband, the radios of the gNBs, and even the frequency, which is very interesting in terms of deployment and usage of resources, resulting in a very sustainable architecture implementation. A Neutral Host approach ensures that a third party manages the gNB resources equally in terms of configuration, hardware, and frequency usage. Contrarily, the classical MOCN approach, where one MNO owns the site and another MNO is merely a guest, usually leads to performance disadvantages for the latter. 5GMED implements a realistic scenario in which two different MNOs use their own 5G network infrastructure, and a Neutral Host operator acts among them, managing the parametrization in the 5G RAN and the 5G Core to optimize the roaming process. Figure 7 illustrates the 5GMED Neutral Host approach deployed in the cross-border scenario. The idea is to implement a MOCN scheme where a neutral host operator manages the configuration of the gNBs and the 5G Cores that need to interact in the cross-border situation.

To implement the roaming optimization techniques, the neutral host strategy of 5GMED is paramount. This strategy is twofold:

- **Re-use of radio network infrastructure via MOCN (RAN Sharing):** MOCN functionality allows a network operator (or neutral host) to share its radio access network with other operators, thus reducing the infrastructure CAPEX and OPEX needed to deploy coverage for more than one operator in a certain area. Each MNO operates its own core network. In particular, 5GMED will show this type of network sharing on the French side of the corridor, where 5G coverage is provided through an agreement with the French operator Free Mobile. Free Mobile sites will be both connected to Free commercial core and at the same time to 5GMED core.
- **First radio node in each side of the border deployed by a Neutral Host:** to configure additional radio parameters (neighbour cells information). This is important to reduce the interruption time when roaming. If both nodes belong to the same neutral host operator, the alignment and configuration of these parameters is highly simplified vs the classical approach of two MNOs.

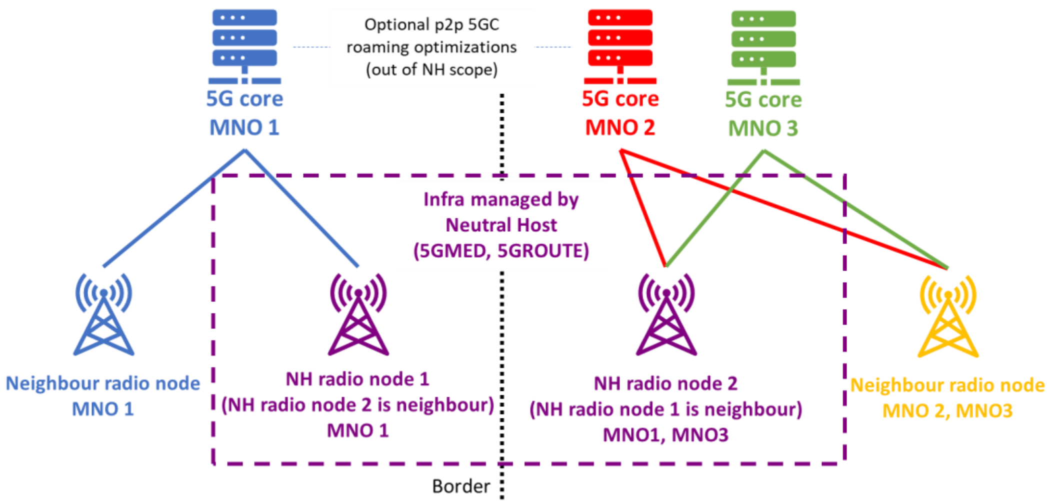

Figure 7 Neutral Host approach for roaming optimization.

4. Service continuity and network performance

The performance of the 5G SA networks of 5G-Blueprint, 5GMED and 5G-ROUTES were evaluated through several measurement campaigns. The measurement included both service and network Key Performance Indicators (KPIs). In the following, we provide the network performance of the three projects in terms of downlink and uplink throughput, round trip time (RTT), reliability, and most importantly, mobility interruption time when moving from one PLMN to another, which demonstrates how much the 5G networks and seamless roaming solutions can guarantee service continuity. It should be noted that the obtained results in the three different projects are not totally comparable. This is expected for many reasons: different deployments, different equipment used, different orography, and different measurement methodologies.

4.1. Interruption time

In the three projects, the mobility interruption time was reduced to values between 70 ms and 300 ms depending on the environment and the technology used. The results obtained in each project are presented in Figure 8. In 5G-Blueprint and 5G-ROUTES, mobility interruption time measurements were recorded for home-routed roaming, while in 5GMED, measurements were collected for both home-routed roaming and local breakout roaming.

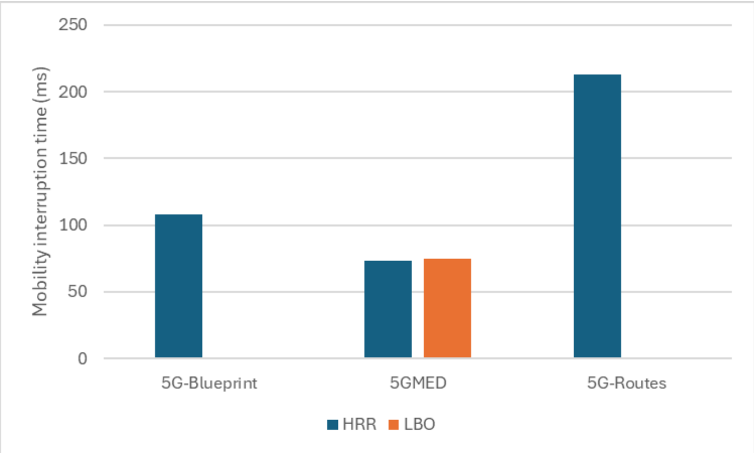

Figure 8 Average mobility interruption times obtained by the three ICT-53 projects 5G-Blueprint, 5GMED and 5G-ROUTES.

It should be noted that the network configurations used in the different projects, the environment where they were they are trialled, and the way the interruption is measured do not allow the comparison one-to-one between the three projects.

In 5G-Blueprint, the service interruption time was measured at the Core network level, as a time needed for signalling process between two Core instances to finalize and to establish a PDU session in the destination network. The average and 95th percentile of service interruption time are both significantly below 150ms, which can be considered unnoticeable and as such crucial for safe teleoperation.

In 5GMED, the interruption time measurements have been obtained from the handover events collected with Nemo Outdoor [11]. It collects the durations of the interruptions caused by the inter-PLMN handover in the data-plane. The average and the 95th percentile interruption time were well below the 100 ms requirement.

In 5G-Route, the network interruption time was measured from AMF logs (N2 type handover), in parallel to this, AT-commands were used from the modems to observe the PLMN change as well as the Ping tests were executed to monitor the reconnection. The measured interruption time is approximately 213 ms on average. Note that two types of handovers defined by the standard were tested: N2 and Xn. While Xn can result in lower interruption times, N2 is considered to provide realistic results with two separate networks as well as in a more secure manner.

From the results shown above, the interruption time has dropped from several seconds or even minutes in the actual deployment of 4G/5G networks to couple of hundreds of milliseconds in the worst case. This level of interruption time is acceptable for most of automotive services and will enable service continuity even when crossing country borders. In addition, the obtained interruption time is lower than the ones obtained in the ICT-18 projects [4] for 5G NSA networks (although it cannot be fairly compared as they are evaluated in different environments and configurations) especially in the case of 5GMED and 5G-Blueprint where the median interruption times are around 75 ms and 108 ms respectively, whereas in the ICT-18 projects the lowest interruption was around 121 ms.

Furthermore, it can be noted that the interruption time when HRR was used is slightly lower than the one obtained when LBO was used in 5GMED. In general, it is expected to have lower latency in HRR as the LBO roaming requires more exchange of signalling messages, but due to the proximity of the two cores in 5GMED the difference between the two interruption times where around 2 ms only.

4.2. Network performance

The three projects were evaluated extensively through different KPIs, in particular, RTT, throughput, and positioning accuracy. The latter is only valid for 5-ROUTES. Figure 9 and Figure 10 show the median RTT latency and throughput obtained by the three projects.

In 5G-Blueprint, the latency was obtained during 500 RTT measurements, which were collected during ping tests initiated from the client side (user equipment in the remotely operated cars/trucks and vessels) towards the servers running on the cloud (remote control services). The throughput was measured using iperf3, with an iperf3 server located in the same cloud environment as in the case of above-described latency measurements. The results are obtained during the trialling activities in the cross-border area on both. Concerning the results, it has been noticed that the UDP uplink throughput is higher on the Belgium side of the border, which is explainable by the fact that the telco operator was using an active antenna that yielded better performance. As seen in the figures, the obtained results for both uplink throughput and end-to-end latency can be considered sufficient for achieving safe teleoperation across country borders and are in alignment with the requirements mentioned earlier. Some further improvements in end-to-end latency can be obtained by placing application functions (teleoperation services) on the network edge to avoid home-routed roaming, but this is out of the scope of the 5G-Blueprint project and should be explored further.

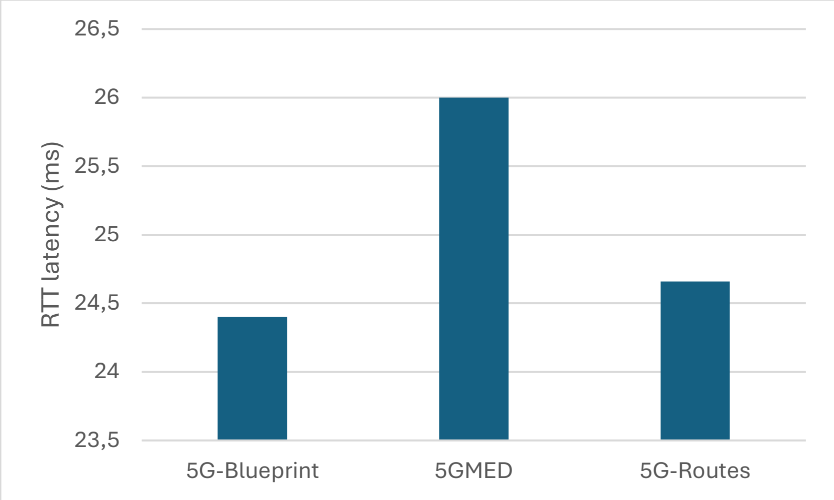

Figure 9 Bar diagram of the average RTT latency obtained in the three ICT-53 projects.

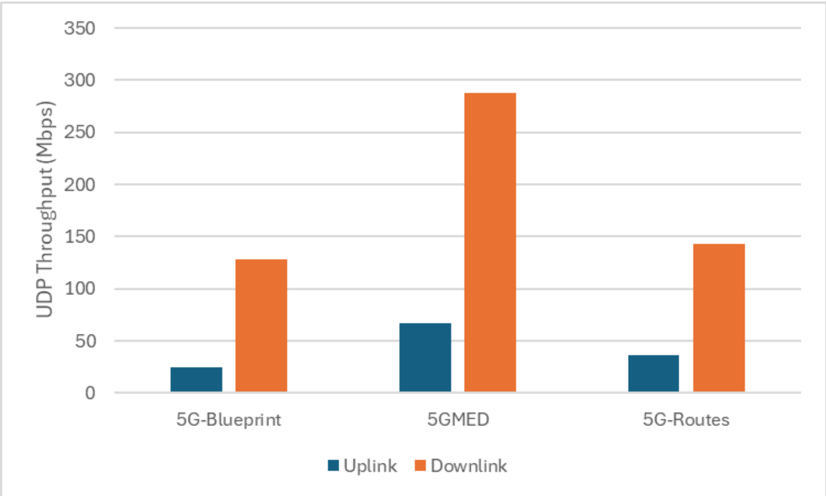

Figure 10 Bar diagram of the median UDP throughput obtained in the 5G-Blueprint and 5GMED.

In 5GMED, the latency was obtained from 100 RTT measurement samples by sending periodic "ping" commands at intervals of 100 ms from the UE to the IP address of the centralized UPF of the home 5G network. The throughput was obtained from 100 measurement samples using IPerf3 with UDP traffic. An IPerf3 server is located on an application server connected to the centralized UPF of each 5G SA network, while an IPerf3 client runs on the laptop of the KPI collection tool, generating new throughput measurements every second. These measurements were conducted with the UE positioned in five Spanish 5G cells and three French 5G cells. As can be observed, the median RTT values fall within the range of 20 ms to 30 ms across all gNBs, which is sufficient to run the 5MED services on the highway. Furthermore, the average throughput values in downlink are way above t the requirement of 100 Mbps but the median uplink throughput is around 66 Mbps. This difference between uplink and downlink throughput is due to TDD frame pattern in Spain (DDDSU) and in France (DDDDDDSUU) with clear unbalance towards downlink.

In 5-ROUTES, the network latency was measured based on the ping tests. The ping was done against different servers (one located inside the 5G core, google server etc.). In addition, to obtain the comparison against the local MNO network, latency tests were measured from a server (located in Tallinn at a distance of about 230 km), this server is widely used by the local MNOs, these results are presented below. The average round trip time (RTT) latency measured is 25 ms. It is important to note that, due to the project-specific 5G-ROUTES network configuration and the underlying communication infrastructure topology, particularly the data path routing, the RTT latency in Latvia exceeds twice as that of Estonia (In Estonia the 6G MHz bandwidth was shared with Telia Estonia and in Latvia only 25 MHz was available). In terms of throughput, the project's maximum target is 10 Mbps. The downlink bandwidth is larger; therefore, application's throughput and performance are primarily limited by the uplink. In Estonia, uplink throughput can easily exceed 10 Mbps and even reach 15 Mbps. However, in Latvia, uplink resources are more limited and maintaining speeds higher than 10 Mbps is not guaranteed in all locations. As for the 5G integrated GNSS-RTK positioning error, three variations of RTK status—Fixed, Float, and Satellite-Based Augmentation Systems (SBAS)—were recorded and reported using the Septentrio MosaicHAT software. Latitude values were analyzed as they represent the 'worst-case estimated position error,' consistently exceeding longitude values. The results showed estimated position errors of up to 3.5 cm (RTK Fixed), 29.3 cm (RTK Float), and 45.6 cm (SBAS). Notably, on the Estonian side, the estimated position error was less than 10 cm, while on the Latvian side, it was in the range of tens of centimetres.

4.3. Latency improvement with LBO roaming and MEC

In 5GMED, specific tests were conducted to evaluate the performance improvement brought by edge computing and LBO roaming in terms of latency. Table 2 shows the average RTT measured under two scenarios: (1) using HRR, which involves communication between the UE and a server connected to the centralized UPF, located 155 km away from the cross-border corridor, and (2) using LBO roaming, where the UE communicates with MEC servers located within the cross-border area and connected to the distributed UPFs. The UE was equipped with a Spanish SIM card. As shown in the results, the average RTT between the UE and MEC is significantly lower (approximately 8–9 ms) compared to the RTT between the UE and the centralized UPF. Moreover, when using HRR, the average RTT observed for the UE connected to the v-PLMN (French network) is not significantly higher than the RTT observed when connected to the h-PLMN (Spanish network). This similarity is attributed to the close proximity of the servers hosting the Spanish and French 5G Cores in Castellolí, which results in negligible differences in average RTT.

Table 2 Average round-trip time using Home Routed Roaming with centralized UPF vs. Local Breakout Roaming with distributed UPF and MEC.

5G Network	Home Routed Roaming (Centralized UPF)	LBO roaming (distributed UPF/MEC)
Spanish (h-PLMN)	24.85 ms	16.54 ms
French (v-PLMN)	25.10 ms	17.96 ms

5. MEC Federation and Orchestration

In cross-border scenarios, MEC federation refers to the interconnection of MECs of different MNOs to ensure a consistent delivery of services across international borders. This allows different MNOs to collaborate seamlessly and share resources, enabling a more efficient and scalable MEC ecosystem. Two approaches were considered: Operator platform–based solution in 5GMED and two-domain approach in 5G-ROUTES.

In 5GMED, a federation interface that allows orchestrators of different administrative domains (i.e., Spain and France in our case) was implemented to share information about the status of the underlying edge infrastructure and the MEC services. The proposed approach is based on the use of an Operator Platform (OP), as per GSMA's definition [8], acting as a MEC orchestrator, thus facilitating control procedures, such as application onboarding, application lifecycle management and network information acquisition through ETSI MEC APIs, among others. In addition, this layer can potentially enable the communication between two MNOs (or two OPs) through an East-Westbound Interface (EWBI), using a REST API model [9]. The EWBI defines a set of essential resources for specifying and deploying cloud-native applications across diverse MEC sites [10]. Standardized API resources include operations related to federated processes involving the aforementioned OPs and infrastructure hosting applications, operations focusing on the infrastructure, specifications about the application, and operations for onboarding and deploying applications. These resources can relate to the infrastructure, applications, or the MECs and the infrastructure hosting applications. In a nutshell, the EWBI facilitates communication between both MNOs' MEC systems, enabling collaborative operations on available edge nodes, sharing application specifications, and performing deployment operations.

The process of MEC federation between two orchestration platforms can be divided into three phases: (i) federation setup, (ii) federation in process, and (iii) federation termination. It is worth noting that federation setup and termination are phases that take place offline and involve also business agreements between the operators, while the federation in process is the actual phase where all the orchestration action can take place. More specifically, during the federation setup phase, the visited MNO adds the home MNO to its database. This action generates a pair of credentials for authentication, which are shared with the home MNO. Then, using these credentials, the home MNO adds the visited MNO to its database and federation is established between the home and visited MECs. During the federation in process phase, the home MNO can deploy an application on the MEC of the visited MNO. This phase ensures the smooth operation of the federation and monitors its performance. Finally, in the federation termination phase, the home MNO can undeploy the federated service and terminate the whole federation session.

A realistic use case for the application of federation through the EWBI is depicted in Figure 11. In this scenario, It was assumed that each country has its own edge infrastructure and an edge orchestrator (based on the NearbyOne tool). The federation setup described above has been completed between the two orchestrators, enabling the EWBI functionality. In addition, the MNOs of each country have deployed distributed UPFs (dUPFs) in each edge server to enable local break out (LBO) towards the MEC application that is running at the edge. In the deployed scenario,it was assumed that a mobile user at the Spanish side is consuming an edge application that is located at the Spanish edge (step 1). As the user is approaching the border (step 2), the location coordinates, which are continuously transmitted to the Spanish orchestrator, trigger the initiation of the service migration. Hence, the service migration is initiated through the EWBI (step 3) and the MEC application is deployed in the French edge. Once the user passes the border (step 4), she is able to connect to the MEC application of the French edge, again through the dUPF and LBO.

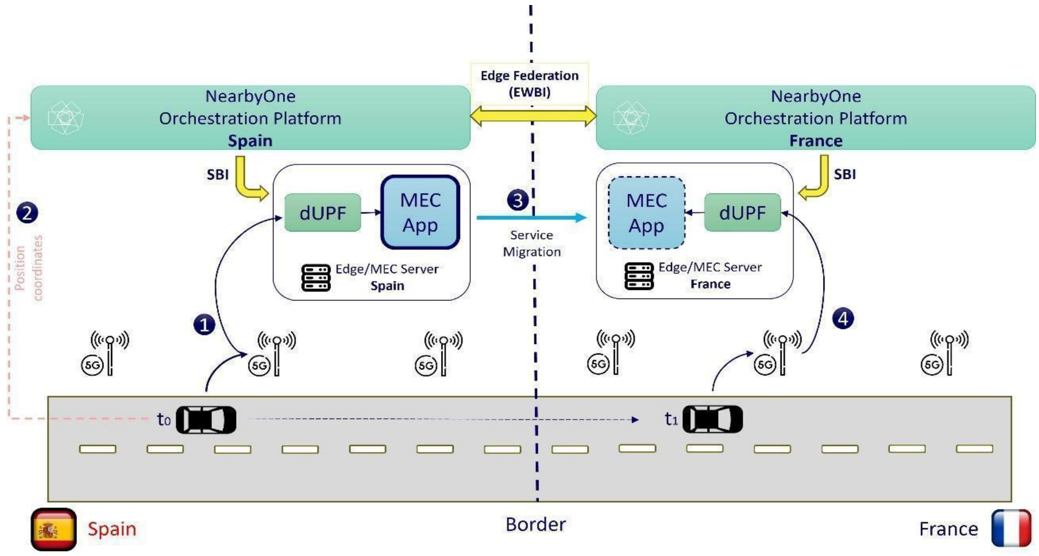

Figure 11 Realistic use case for the application of federation through the EWBI in 5GMED.

The two-domain approach setup used in 5GROUTES is depicted Figure 12. This setup consists of a set of Intel Next Unit of Computing (NUC) mini-PC elements, divided over two domains (one for Latvia and one for Estonia). Each domain contains a NUC acting as Network Functions Virtualization Orchestrator (NFVO) and NUCs with an all-in-one kubernetes, where technological enablers and CAM services backends are executed. Each of the domains is connected to a different UPF element serving the different PLMN IDs. Owing to configuring an extra NUC as DNS and a set of MikroTik network routers, the traffic from UEs traverses each UPF and is directed to the corresponding enabler/backend instance belonging to the network domain. For instance, a UE attached to gNB with PLMN 24701, corresponding to the Latvian domain, will flow through the edge UPF and it will reach enablers of CAM services platform running in the Latvian domain. Then, the traffic of a UE attached to gNB with PLMN 24827, corresponding to the Estonian domain, will flow through the UPF, labelled as core UPF, and reach technological enablers/CAM backend instances of CAM services platform running in the Estonian domain.

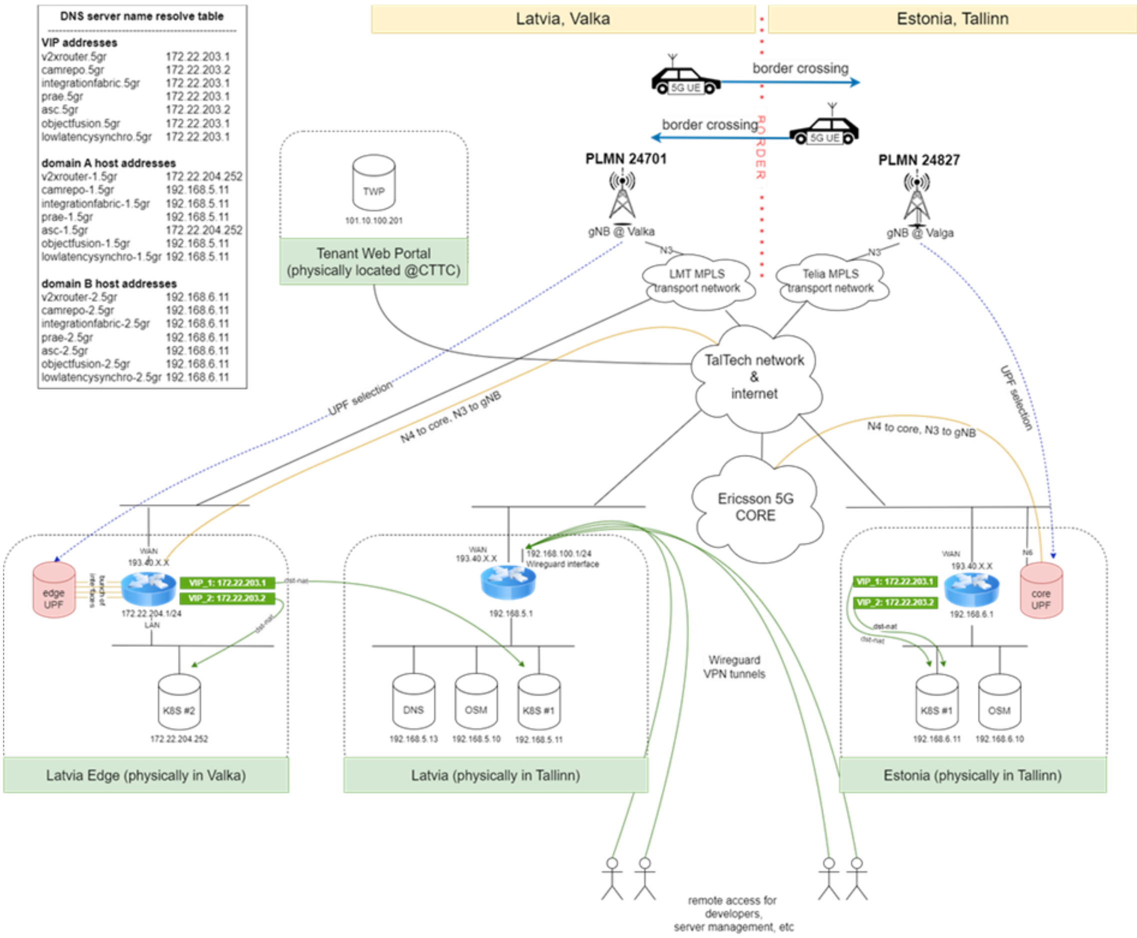

Figure 12 5GROUTES two-domain approach setup.

6. Conclusions and challenges

The obtained results in the three ICT-53 projects (5G-Blueprint, 5GMED, and 5G-ROUTES) have shown the unlocked potentials of 5G SA networks in guaranteeing seamless connectivity for automotive services, especially in cross-border scenarios. The three projects were able to show that interruption time when crossing borders (or changing mobile networks) from couple of minutes in current commercial deployment to around 100 ms, which is crucial for the automotive vertical. This result was obtained by two different approaches in the core network. Two 5G standalone networks with N14 interface, developed in 5G-Blueprint and 5GMED, and multi-operator core network, developed in 5G-ROUTES. Furthermore, the three projects deployed RAN optimization by configuring the cell at the two sides of the borders as neighbour cells. The three projects demonstrated the stability of the home routing solution combined with inter-PLMN handover. In addition, 5GMED was able to successfully deploy LBO roaming, which lead to efficient deployment of MEC across two PLMNS and therefore a reduction in the application's latency.

Another key takeaway is the feasibility of RAN sharing. The 5G-ROUTES and 5GMED projects successfully shared the RAN of a commercial mobile network operator, utilizing the same Base-Band Unit (BBU), Radio Unit (RU), and spectrum while ensuring complete traffic isolation between networks. This outcome highlights the possibility of conducting trials with minimal equipment. Furthermore, the concept of neutral host was shown at the gNBs of the two operators across the border to enable the joint configuration of the neighbouring cells of the two operators. Without this joint configuration, inter-PLMN handover was not possible.

Despite the promising results, the deployment of the solutions was not straightforward and required the endeavour of different solutions to overcome several complex challenges. These challenges are: TDD pattern and frequency, uplink capacity, N14 interface deployment, LBO implementation, commercial user equipment limitations, radio network dimensioning and planning, and open-source edge UPF integration.

6.1. TDD pattern and time synchronization

One of the main challenges faced in the configuration of the Inter-PLMN handover in 5GMED was the different TDD patterns employed by the two PLMNs across the international borders (e.g., French and the Spanish Networks). The GSMA recommends 3 different TDD patterns (with different uplink to downlink ratios) in commercial networks, each one has different characteristics to optimize uplink and downlink traffic [12]. In each country, the national regulator selects one pattern to be used for public networks. This is recommendable to avoid the presence of different patterns adjacent to each other, which can lead to service degradation. In fact, the GSMA recommended the use of the same frame pattern at national level and even at international level whenever possible to avoid cross-border issues. Despite this recommendation, many countries have different TDD patterns as in the case of France and Spain; the selected pattern in Spain is DDDSU and the one in France is DDDDDDDSUU. This difference in the frame structure has in impact in the Inter-PLMN handover between two networks using different frequencies. In practice, a UE in the home network will not be able to scan the Synchronization Signal Block (SSB) of the visited network with different TDD pattern, and the consequence the UE will not be able to perform the handover between the cells of the two countries as shown in Figure 13. Aligning the frame structure is not an option as it breaks the national regulations.

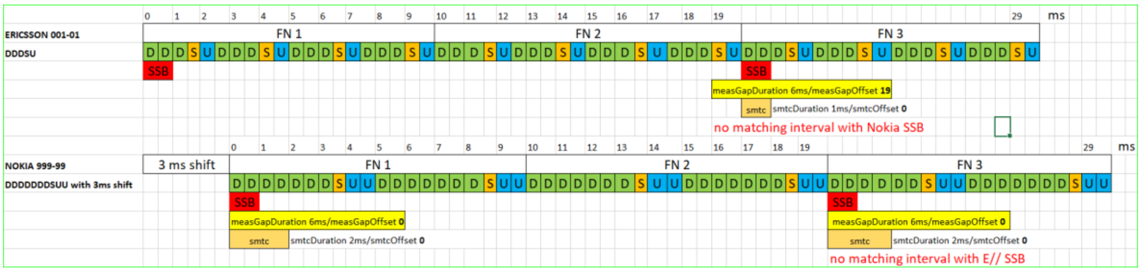

Figure 13 Example of non-aligned TDD patterns.

The solution was to align the following parameters as shown in Figure 14:

- Modify the gapOffset & smtcOffset in the French network (Nokia gNb) for Inter-Freq handover configuration to align with the SSB (Synchronization Signal Block) of the neighbour cells containing information about the frequencies employed by the neighbour Cell in Spain.
- Modify the SMTC duration in the Spanish node (Ericsson)

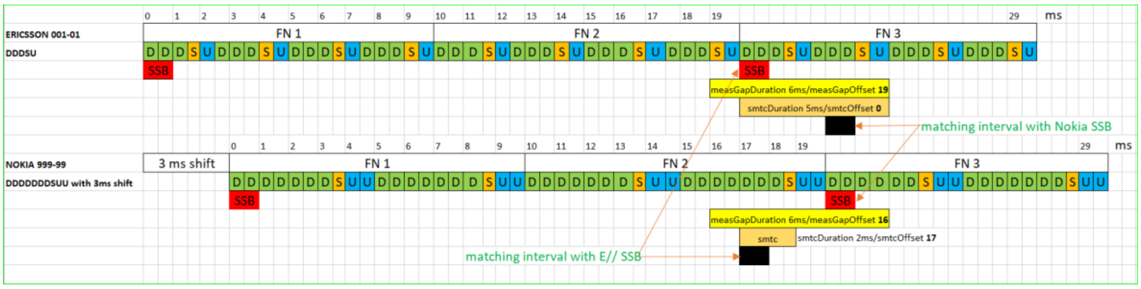

Figure 14 Aligning the TDD patterns of the two PLMNs.

The implemented changes to enable inter-Frequency and Inter-PLMN handover apply only to the cross-border nodes between the two countries Perthus FR with Perthus SP and Junquera with the Tunnel. The other gNBs in each country are not impacted.

This solution was a specific solution in 5GMED where the Neutral host concept was considered. However, this solution cannot be easily generalized and more generic solution, which could be related to simplifying cross-border deployments by aligning regulatory frameworks between countries, including spectrum allocation, power limits, and TDD frame harmonization.

6.2. Uplink capacity

Although the 3GPP allow the use of all slot format combinations (i.e., allocation of time slots to uplink or downlink) [13], the GSMA recommends the use of only 3 combinations and one combination in each country as mentioned in Section 6.1. This will result in a static uplink to downlink capacity ratio whatever the characteristics of the traffic demands. Moreover, the recommended combinations are thought to accommodate legacy traffic such as video streaming, video conferencing, web browsing, etc. This is why it is biased towards much higher capacity in downlink than in uplink (i.e., at least a ratio 3:1 in the recommended combinations of GSMA).

When it comes to large-scale deployments of teleoperated vehicles, it is becoming essential to dimension the network properly to offer higher uplink throughput for multiple parallel camera streams. This also applies to many CAM services where more uplink traffic than downlink traffic is required. This mismatch with the current network configuration is challenging especially that automotive services will be using not only one but all public networks.

6.3. N14 interface implementation

In 3GPP standard, the N14 interface is defined as an interface between AMFs within the same PLMN [5]. The corresponding signalling flow is also provided in the same standard. In addition, the same standard defines the architecture and the signalling flow for the HRR. However, the detailed signalling flow when using N14 during the roaming process, which was proposed in [14], is not provided in the standard. Therefore, custom deployment of N14 interface was deployed in 5GMED [6] and 5G-Blueprint [7] by combining the procedure of HRR roaming and N14 signalling described in [5]. In addition, the LBO roaming process with N14 interface is not available in the standards.

The commercial deployment of such solution requires efforts in standardization to provide all the tools and procedures to be implemented in the networks.

6.4. LBO implementation

To provide automotive services with continuous low and controlled latency, the service application should be deployed as close as possible to the connected vehicle. This can be achieved by connecting the latter to the closest MEC. In the cross-border scenario, this will mean that user traffic must not be forwarded to its home UPF as in the case of HRR. Therefore, LBO roaming becomes a requirement in such cases. However, the deployment of LBO *roaming* accompanied with MEC deployment is not straightforward and requires careful design of the network. In fact, the end user application must be aware of the network change and the new IP address of the application server located at the MEC of the visited network. In a commercial network, a new PDU session is established as consequence of the roaming, and the UE application can trigger a new DNS request to be redirected to the closer MEC. However, with the seamless inter-PLMN handover mechanism, the UE application is not aware of this network change because the PDU session is not re-stablished. To overcome this challenge, 3GPP standard [15] proposes different Session and Service Continuity (5G SSC) modes to support multiple continuity requirements when different UPFs are involved.

- **SSC Mode 1**. Network preserves the connectivity service provided to the UE. PDU session and IP address are preserved throughout the lifetime of UE mobility. Here the PDU session anchor UPF is maintained throughout the session's lifetime. In the case of roaming, this corresponds to the HRR scenario.
- **SCC Mode 2**. In this mode, the network may release the connectivity to UE and may also release PDU session. In this case, the IP address will be changed during re-allocation. If a new PDU session is established, then a new anchor UPF will be created.
- **SCC Mode 3**. In this mode, network makes sure to provide no connectivity loss to UE. If a new PDU session is required, then a new PDU session anchor point is established

before the previous connection is terminated. This will help in better service continuity especially in the case of LBO roaming.

Unfortunately, mobile networks and UE currently support only SSC1. Therefore, the possibility of evaluating SSC Mode 2 and Mode 3 that could potentially solve the issue was discarded.

An alternative solution that overcomes this challenge without impacting the network consists in initiating a DNS request when the UE is roaming. This requires changes in the application layer that should be able to change the destination IP address by issuing a DNS request each time a UPF is changed. The problem gets even more complicated in cross-border scenarios when the UE is moving from one PLMN to another PLMN with a different DNS.

Another solution can be the definition of a Local Area Network (LAN) with the same sub-network address that is connected to each UPF and have the server for a given service always with the same IP address. In 5GMED, this solution, which is transparent to the UEs and applications, was adopted.

In addition to the technical challenges related to LBO, the adoption of such procedure is not taking place as it requires the transfer of all signalling (including billing) from the home network to visited network. Here regulations can be crucial to enforcing such solution.

6.5. Commercial user equipment limitations

To enable inter-PLMN Handover, a UE located on one side of the border must be capable of scanning neighbouring cells on the opposite side. During field tests (e.g., in 5GMED), different models of UEs exhibited diverse behaviours depending on the 5G chipset integrated into the device. While the Exynos-based UEs (e.g., Samsung S21 smartphone) were able to scan neighboring cells in both directions (e.g., Spain to France, and vice versa) without the synchronization of TDD patterns (see Section 6.1), Qualcomm-based UEs (e.g., Samsung S23, Quectel RM500Q and RM520 modems, and Askey CPE) failed to scan neighbouring cells in one of the direction (e.g., when roaming from Spain to France in 5GMED).

The issue was solved in 5GMED with the synchronization of TDD patterns. However, this needs more thorough investigation on the capabilities of the 5G chipsets to enable the seamless roaming without the need to change network configuration.

6.6. Radio network dimensioning and planning

The results obtained in all different pilot sites, including the cross-border site, show that the 5G SA network in the 3.5GHz range offers a significantly limited range with a good and stable signal quality (which proved to be up to 2km away from the gNBs in 5G-Blueprint for instance). Furthermore, the trials emphasized the importance of radio coverage optimization in preventing handover issues such as the "ping-pong" effect, where user equipment continuously switches between two networks. Addressing these issues is crucial to ensuring seamless connectivity and optimal network performance. In addition, the irregular orography in some cross-border sections (e.g., French-Spanish borders) poses significant challenges to ensuring 5G coverage continuity. This result highlights the importance of careful network dimensioning. In the case of cross-border scenarios, additional collaborative planning between the operators is needed. This can be done through neutral host concept for instance. In this case, the neutral host will jointly configure the cells at the border. This can include but not limited to: i) configuring the two networks as equivalent PLMNs; ii) configuring the cells on the two sides of the border as neighbour cells; iii) adjusting coverage through transmit power, tilt configuration, and antennae directions; iv) and synchronizing the TDD frames as explained in Section 6.1.

6.7. Open-source edge UPF integration

Throughout the 5G-ROUTES project, various solutions were thoroughly investigated to enable edge UPF integration. In particular, open-source edge UPF solutions were explored, with three promising candidates identified: Open5GS, eUPF Project, and Fraunhofer Open5GCore. However, none of these solutions fully functioned with the 5G SA core, primarily due to communication issues with the SMF. The main challenges in integrating open-source edge UPF solutions included protocol and signalling incompatibilities (e.g., SMF conflicts, packet forwarding issues) and a lack of fault tolerance and redundancy, where a single failure could lead to a full system failure. As a result of this investigation, the project ultimately decided to proceed with an alternate solution which is based on UE-assisted breakout based on multi-DNN solution for demonstrating multi-domain CAM platform solution.

6.8. Remaining challenges

What remains to be further investigated in the context of inter-PLMN handover optimizations are i) advanced security procedures; ii) automated provisioning; and iii) network slicing continuity.

Regarding security, using the Security Edge Protection Proxy (SEPP) was out of the scope of the three projects, where the 5G Core instances were connected directly. Still, it would be relevant to further consider and evaluate the possible impact.

The automated provisioning refers to the up-to-date RAN configurations that are necessary for neighbouring cells at the border location, as the neighbouring gNBs need to be configured as equivalent PLMN. In the three projects, this configuration was manual and as such doable due to the limited number of radio sites in the cross-border area, but a large-scale deployment would require an automated approach with secure sharing of sensitive information such as frequencies, physical cell IDs, among others.

One solution to guarantee service continuity across different networks with different loads and characteristics is network slicing. By using network slicing, automotive vertical traffic can be isolated from other traffic in the network and though the required quality of service can be guaranteed more easily and efficiently. However, one of the challenges that was not investigated yet is the continuity when crossing the border and transitioning between two different networks. One solution to this problem could be through the concept of slice federation proposed in 5GMED [16]. The slice federation enables the extension of network slices across different operators' networks. The concept of slice federation allows users to seamlessly access services and maintain a consistent network experience when moving between different operators' networks. However, in the case of network slice roaming, the Operator Platform (OP) concept has not yet proposed any mechanism for federating slices.

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