Cross-border 5G Seamless Connectivity for Connected and Automated Mobility: Challenges, Network Implementation, and Lessons Learnt

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***Abstract*—The delivery of continuous and seamless Connected and Automated Mobility (CAM) services across international borders poses substantial challenges due to the complex interactions among 5G mobile network operators (MNO), road and rail infrastructure operators, neutral host operators, and end users, at both sides of the border. Some of the most prominent challenges include achieving roaming with short-enough interruption time and low latency, and providing cross-MNO orchestration and network slicing continuity. The EU-funded Horizon 2020 5GMED project has devised a cross-border network architecture that directly addresses such challenges in smart mobility use cases across the Spanish-French border. This paper presents an overview of the 5GMED use cases, technical challenges, and ongoing research and development efforts. It provides implementation details and lessons learnt from the project's small-scale and large-scale trials that revolve around four use cases: remote driving, road infrastructure digitization, future railway mobile communications, and follow-me infotainment.**

***Keywords*—5G, cross-border, mobility, architecture, CAM, trials.**

I. Introduction

In the last few years, substantial research and economic efforts have been devoted to developing and testing Cooperative Intelligent Transport Systems (C-ITS) technologies, including Connected and Automated Mobility (CAM) and Future Railway Mobile Communications Systems (FRMCS). It is deemed critical to develop holistic models for the evolution of open, smart and data-driven sustainable mobility that combine both technological and governance aspects. To advance on the implementation of the ambitious European strategy on C-ITS, the European Commission (EC) emitted a communication highlighting a set of service deployment priorities [1]. The aforementioned communication referred to the lack of EU-wide interoperability as one of the main challenges in the successful implementation of its C-ITS strategy. In this regard, the European ITS Committee regards cross-border testing as one of the main priorities in its roadmap [2].

5G is an enabler of high mobility and densely connected CAM and FRMCS use cases, where features such as ultra-low latencies, very high data rates, and wide spectrum availability are required. [3] provided a comprehensive survey on the application of 5G to advanced vehicle-to-everything (V2X) use cases, and presented a review of the most important enabling technologies e.g., as mobile edge computing (MEC), network slicing, and so forth. The authors also highlighted various research and implementation challenges, such as radio communication channel phenomena, frequent handovers, fetching mechanisms, management of computational resources, etc. Additional challenges arise in cross-border scenarios, where the interactions among 5G mobile network operators (MNO), road and rail infrastructure operators, neutral host operators, and end users at both sides of the border introduce additional complexity and must be suitably managed. The work in [4] presented three European projects conducting deployment studies on 5G for CAM on cross-border corridors, and provided a comprehensive gap analysis identifying elements for further study related to e.g., diverse service requirements, integration of non-terrestrial communications, coverage planning, etc. Moreover, low latency is required to enable both CAM and FRMCS use cases, and roaming operations should yield short-enough interruption times. Additionally, cross-MNO orchestration and network slicing continuity are also required to support cross-border mobility. In this regard, the EU-funded Horizon 2020 5GMED project has devised a cross-border network architecture tailored to tackle the unique challenges posed by smart mobility scenarios along the Spanish-French border [5].

In this paper we present an overview of the 5GMED project in Section II, including an introduction to the project's use cases in Section III and technical challenges of cross-border scenarios in Section IV. The ongoing research and development efforts, including the network implementation details, are presented in Section V. Finally, lessons learnt from the project's large-scale and small-scale trials are also discussed in Section VI and Section VII concludes the paper.

II. 5GMED Project Overview

The 5GMED project is an initiative supported by funding from the European Commission's Horizon 2020 research and innovation program within the framework of the 5G Public Private Partnership (5GPPP). Its primary objective is to assess the capabilities of 5G technologies (specifically 3GPP Rel.16) in fulfilling the requirements of CAM and FRMCS services in cross-border scenarios. 5GMED is conducting extensive 5G connectivity trials along the Mediterranean cross-border corridor between Figueres (Spain) and Perpignan (France). To enable these trials, 5G Stand-Alone (SA) network infrastructures have been deployed in both Spain and France, providing 5G coverage along a 65 km stretch of the highway and high-speed rail track, which includes a cross-border railway tunnel.

5GMED is also carrying out small-scale trials in automotive testbeds in Castellolí (Spain) and Paris-Satory (France). A segment of the rail track within the cross-border area will also be used for trials involving a low-speed maintenance train. These small-scale trials serve the purpose of verifying and validating the functionality of the services and the 5G network architecture before transitioning to the large-scale trials.

III. Use Cases

The 5GMED project focuses on four distinct use cases that are being implemented, tested, and showcased during both the small-scale and large-scale trials. These are described below.

A. Remote Driving

This use case aims to offer remote assistance to a Connected and Autonomous Vehicle (CAV) upon intricate traffic situations beyond its operational design parameters. These situations include adverse weather conditions, accidents, transitioning from highways to urban roads, undefined traffic conditions, etc. In such situations, the CAV requests remote assistance from a tele-operation center, and a remote driver takes control of the CAV until it reaches a safe location, from which the vehicle resumes autonomous operation. During remote driving, the CAV transmits video images and sensor data (e.g., Light Detection and Ranging - LiDAR, 360º camera, etc.) up to the remote station, while commands are sent down from the remote station to the vehicle's actuators. It is crucial that both ends receive such data with extremely low latency and a high level of reliability. Therefore, the design of the 5G network must cater to these Quality-of-Service (QoS) requirements, which become particularly critical when the CAV crosses international borders.

B. Road Infrastructure Digitalization

This use case aims to establish an intelligent Traffic Management System (TMC) to ensure the safe and efficient flow of traffic on highways where Connected Vehicles (CVs) share the road with traditional non-connected vehicles. This relies on cooperative sensing, and data aggregation from CV sensors and external sources like traffic cameras and roadside sensors. A TMC processes this data and generates intelligent traffic management strategies, which are then transmitted to the CVs via the 5G network. There are two primary categories of traffic management strategies under consideration: warning traffic strategies and global traffic strategies. On the one hand, the warning traffic strategies are primarily concerned with identifying road hazards (e.g., accidents, stalled vehicles) and promptly relaying warning notifications from the TMC to vehicles approaching these high-risk areas at high speeds. On the other hand, the global traffic strategies involve the TMC analyzing the overall traffic conditions on the highway to detect abnormal behaviors (e.g., traffic congestion, vehicles traveling at unusually slow speeds) and transmitting regulatory commands (e.g., lane changes, speed adjustments) to groups of vehicles traveling in proximity to these areas of concern.

C. Railways Services

FRMCS services are categorized into three distinct groups [6]: Critical Services, to control and monitor train operations and ensure safety; Performance Services to enhance the overall performance of railway operations; and Business Services to support business operations and cater to passengers. 5GMED focuses on performance and business services [7]. Performance services within 5GMED encompass (i) Advanced Sensors Monitoring On-Board, which involves monitoring the status of non-critical train systems through data communication between on-board sensors, ground-based train control information systems, and railway personnel; and (ii) Railway Track Safety, which focuses on the detection of hazards on rail tracks using on-board LIDAR sensors and AI-based processing at the MEC. The business services of 5GMED consist of (i) Wi-Fi for Train Passengers, which ensures high-performance and seamless Wi-Fi access throughout the entire cross-border corridor, including tunnels, and (ii), Multi-Tenant Mobile Service, which uses 5G small cells on board to provide high-bandwidth and low-latency access to a neutral MNO service.

D. Follow-Me Infotainment

This use case aims to efficiently deliver various forms of high-quality media content (e.g., 360º video live-streaming, virtual reality video) in real-time while maintaining a consistently high level of Quality-of-Experience (QoE) and QoS. This service is intended for passengers traveling at high speeds by either car or train along the cross-border corridor. The use case primarily focuses on demonstrating and evaluating the dynamic relocation of Virtual Network Functions (VNFs) responsible for delivering media services to end-users. These VNFs move across different Edge nodes to remain in close proximity to users as they traverse the corridor. It presents challenges related to ensuring uninterrupted service even during VNF migrations, with a strong emphasis on achieving minimal latency and consistently high data rates.

IV. Technical Challenges

Delivering continuous and seamless services in cross-border scenarios poses significant challenges, especially when accounting for mobility issues, particularly as users may cross international borders, thereby transitioning between different Public Land Mobile Networks (PLMNs). These PLMNs in different countries are typically managed by different operators. In existing network deployments, there is limited cooperation and information exchange between PLMNs, primarily focused on roaming procedures. Consequently, achieving the objective of providing uninterrupted and seamless services in cross-border scenarios is a complex endeavor. It entails numerous technical challenges, particularly in the realm of mobility within cross-border regions, which we present in this section.

A. Challenging Environment and Heterogeneous Radio Access

The Perpignan-Figueres cross-border corridor encompasses rural areas of uneven terrain and dense vegetation. Moreover, a segment of the cross-border rail track extends through an 8 km tunnel in the Pyrenees near Le Perthus. To address the environment-related coverage limitations, it is essential to deploy a specialized network infrastructure that incorporates various radio access technologies to provide services in areas where the 5G network coverage is deficient. The technologies incorporated in 5GMED vary depending on the scenarios considered. In the automotive scenario, C-V2X (PC5 interface) is employed to cover short segments of the highway. Furthermore, for remote and isolated regions within the railway scenario, technologies such as 70 GHz IEEE 802.11ad, and satellite communication are utilized. These additional technologies complement the 5G network, ensuring connectivity even in challenging areas and coverage gaps.

B. Roaming with Low Interruption Time and Low Latency

The movement of User Equipments (UEs) at high speeds leads to a connectivity problems that 5G networks typically resolve when the UE is within the coverage area of its home PLMN (h-PLMN). However, the roaming process typically results in significant interruption times and latency, which are unsuitable for advanced, high-mobility CAM and FRMCS services. In current roaming techniques, the UE will remain connected to its h-PLMN even when it crosses the borders, drives inside the new country, and until the signal becomes extremely weak. At that moment, the UE will scan radio frequencies to locate a suitable PLMN for connection, and this visited PLMN (v-PLMN) must exchange information with the h-PLMN for user authentication. This process results in a service interruption ranging from several hundred milliseconds up to minutes [8], which is unacceptable for most of CAM and FRMCS services. Within a train environment, where the train is moving at exceptionally high speeds and accommodating numerous connected users, this interruption time can be even longer due to the simultaneous roaming of many users. In 5GMED, various solutions at both the 5G core and radio access network (RAN) have been considered to overcome this challenge, as presented in the next Section.

A critical component in 5G networks to achieve low latency is edge computing, which reduces latency by placing distributed computing resources in close proximity to users. In 5GMED, we are deploying distributed instances of the User Plane Function (UPF) within the MEC nodes. Latency becomes particularly critical in cross-border border regions due to the legacy roaming method known as home-routed roaming (HRR) [9]. In HRR, all user data is routed back to the UPF in the h-PLMN, even if the UE is currently within a v-PLMN. This HRR approach is not appropriate for the deployement of edge computing. As all user data is directed to the home UPF, the use of MEC servers loses its effectiveness when the UE is not connected to its h-PLMN.

C. Cross-border Orchestration

5G networks are designed to facilitate service and network function virtualization. This entails the necessity of having one domain orchestrator for each PLMN to manage and monitor the virtualized/cloud-native elements and their life-cycles. In the context of cross-border scenarios, a UE utilizing a virtualized service may need to switch to a different PLMN when crossing the border. This transition demands the allocation of resources and configuration of the same service within the v-PLMN. Consequently, it becomes imperative to establish a cross-border interface between the two domain orchestrators of the PLMNs in different countries. In 5GMED, the GSMA concept of a common Operator Platform (OP) [10] is explored. This leverages federation and enables access to the Edge/Cloud capability of an operator, or even other operators that are part of the federation, by just connecting to a single platform.

D. Cross-border Network Slicing Continuity

Network slicing represents a distinctive feature within 5G networks, enabling the partitioning of a single physical network infrastructure into multiple isolated and flexible logical networks, referred to as slices. These slices can be customized to accommodate the unique demands of diverse users or applications by assembling a variety of resource components, including core, transport, and radio network elements. Network slicing allows different tenants to have their own isolated slices with specific QoS requirements. Although the standardization of network slicing within 5G networks is well-established, the implementation of network slicing across borders presents a particular challenge. The primary issue arises from the fact that different network operators may have distinct slicing policies, configurations, and resource availability. Thus, transferring a slice from one PLMN to another becomes a complex task.

In 5GMED, the slice federation concept is proposed to provide network slicing continuity across different PLMNs, allowing users to seamlessly access services and maintain a consistent network experience when crossing the border.

V. Network Implementation

To address the challenges outlined in Section IV, 5GMED has devised a cross-border network architecture that comprises six distinct layers: network infrastructure, MEC, orchestration, slice management, cloud, and data analytics [5]:

A. 5G SA Networks

Fig. 1 illustrates the internal architecture of the two private 5G SA networks that are deployed and operational in the Mediterranean cross-border corridor between Figueres (Spain) and Perpignan (France). Fig. 1 represents the Network Functions (NFs) located in the 5G Core of both networks, the internal interfaces between these NFs, the interfaces connecting the 5G Cores to their respective 5G RAN in each country, as well as the interfaces that facilitate cross-border connectivity. The two 5G Core instances have been supplied by Druid. They are hosted on separate servers situated in Castellolí, 155 Southwest of Figueres. These 5G Cores encompass essential network functions such as AMF (Access and Mobility Management Function), SMF (Session Management Function), UDM (Unified Data Management), AUSF (Authentication Server Function), a centralized UPF, and distributed UPFs.

The 5G RAN consists of a total of twelve gNodeBs, with six Ericsson gNodeBs located in Spain and connected to the Spanish 5G Core, and six Nokia gNodeBs situated in France and connected to the French 5G Core. Fig. 2a provides an overview of the gNodeB locations in France. Red tower symbols denote gNodeBs utilizing the spectrum from the French operator Free Mobile in band N78. Sites labeled as BTS04 and BTS05, marked with green circles, represent gNodeBs within LFP infrastructure. For gNodeB sites in Spain, as depicted in Fig.2b, a similar arrangement can be observed. Red towers symbolize gNodeBs provided by Vodafone and using band N78 spectrum. Green circle sites represent gNodeBs on LFP towers using band N77 spectrum. A Distributed Antenna System (DAS) has also been installed within the 8-kilometer railway cross-border tunnel. This DAS consists of 23 access points connected via fiber to a Master Unit provided by CommScope. The Master Unit is in turn connected to a Remote Radio Unit and a Baseband Unit

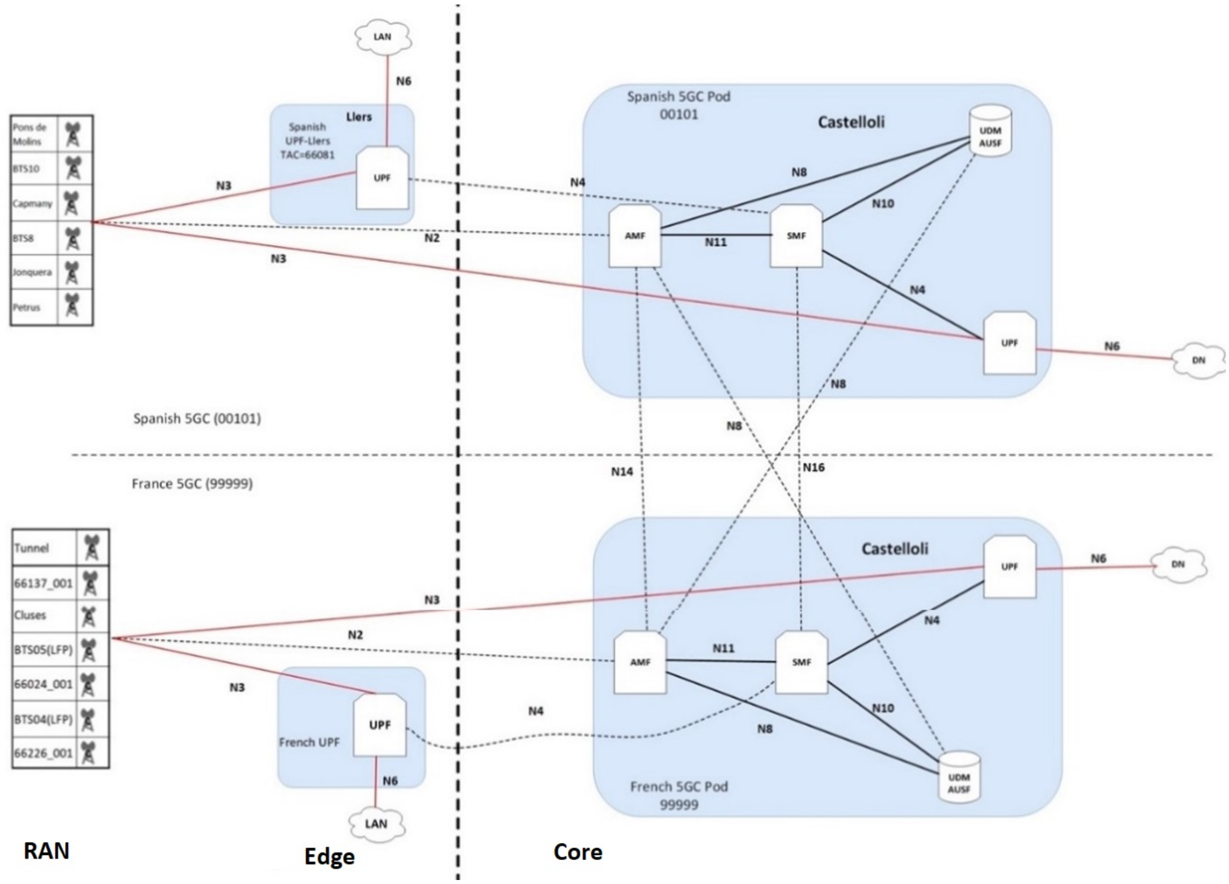

Fig. 1: Internal architecture of 5G SA networks deployed in 5GMED cross-border corridor.

supplied by Nokia. The spectrum allocated for use within the tunnel is provided by Free Mobile in band N78.

The intricate cross-border orography introduces additional complexity to the establishment of the transport network. This network plays a crucial role in enabling connectivity between the gNodeBs positioned along the corridor and the 5G Cores located in Castellolí. The transport network incorporates various technologies, including microwave point-to-point connections and fiber optic links.

B. Roaming Optimization Techniques

In addition to HRR, 5GMED deployed Local Breakout (LBO) roaming technique [9] to overcome the challenge of high latency induced by the HRR. In LBO, the data traffic of the UE stays in the v-PLMN and therefore, the home UPF and SMF will not be involved in the call. Since data traffic is not be forwarded to the home UPF as in the HRR, the end-to-end latency can be significantly reduced. However, the price to pay for this latency reduction is in terms of interruption time; when the UE experiences LBO, it must establish a new Protocol Data Unit (PDU) context with the v-PLMN. This might lead to significant interruption time that is needed to establish this new PDU context. Additionally, the establishment of a new PDU will result in a change of the IP address of the UE, which can be a problem for the continuity of certain applications. Eventually, the two roaming techniques suffer from relatively unacceptable interruption time, especially the LBO. Thus, in 5GMED, several roaming optimization techniques are investigated and applied to reduce interruption time:

- *UE roaming with AMF relocation*: The N14 interface between home AMF (h-AMF) and visited AMF (v-AMF) allows the v-AMF to fetch the UE context from the h-AMF, thus eliminating the need for full attachment and registration. Through the N14 interface, the v-PLMN is made aware of the UPF and IP address of the h-PLMN. The user plane is re-established as part of the tracking area updated in the v-PLMN, reducing the registration/authentication time [12].
- *Reducing failed attachments*: If the v-PLMNs is configured as equivalent PLMN to the h-PLMN in the UE, then the attachment request of the UE in the visited network is guaranteed to succeed.
- *UE roaming with handover*: The gNBs are configured so that those cells across the border are neighbouring cells. The UE will be instructed by the h-PLMN to scan for the quality of the visited network cells across the border, and a network handover is triggered when the handover threshold is crossed. This requires coordination between both networks, e.g., low-level parameters such as cell IDs need to be communicated across networks.
- *Early home network release*: The gNB in the h-PLMN must be configured to release the connection of the UE while there is a good signal level, and an attachment to the v-PLMN can be completed; this must be combined with the previous point. To find the threshold to release the connection, drive test optimizations around the border are executed.
- Network slices to roaming type mapping: Each slice will

be configured with either HRR or LBO roaming. As some services cannot tolerate even short interruption time (e.g., remote driving use case) and others cannot tolerate even low latency (e.g., follow-me infotainment use case), it is necessary to use HRR for the former and LBO for the latter.

With all these optimization techniques, the interruption time is expected to be as low as two hundred milliseconds [12].

C. Cross-MNO Orchestration

The orchestration layer in 5GMED is built around the NearbyOne orchestrator [13], a domain orchestrator (DO) capable of managing the lifecycle of applications and cloud-native network functions. The NearbyOne orchestrator integrates with the 5GMED services that run along the compute continuum, from edge to cloud, and which may require proactive migrations in automotive scenarios. The design of the cross-MNO federation between each MNO's DO follows GSMA's "Operator Platform" (OP) concept [14] to make operators' assets and capabilities consistently available across both networks and international borders (Fig. 3). The implementation in 5GMED targets the East-Westbound Interface (EWBI) that enables the OPs to exchange information about network and service status. The integration of the NearbyOne orchestrator with the EWBI federation API is achieved with a subset of API resources used to define and deploy cloud-native applications:

- *Federation Management*: Defines the relationship between the two OPs to establish an agreement allowing the exposure of the host's resources and capabilities of to the guest OP.
- *Application On-boarding Management*: Registers, retrieves, updates and removes applications towards a partner OP.
- *Application Deployment Management*: Controls the deployment and termination of applications that have been on-boarded on a partner OP.
- *Artefact Management*: Uploads, removes, retrieves and updates application artefacts over EWBI towards a partner OP.
- *File Management Upload*: Removes, retrieves and updates application binaries over EWBI towards a partner OP.
- *Availability Zone Info Synchronization*: Manages the access to host OP availability zones as well as status updates.

D. Slice Management

The 5GMED slice management layer comprises the components shown in Fig. 4. The Network Slice Management Function (NSMF) managemes and orchestrates network slice instances and derived network slice subnet requirements. The Network Slice Subnet Management Function (NSSMF) consists of different sub-components, including: (i) Core Network Slice Subnet Management Function (C-NSSMF), responsible for managing the core network resources; (ii) Radio Network Slice Subnet Management Function (R-NSSMF), which handles the radio network resources through the interface with the RAN controller in the orchestration layer; and (iii) the Transport Network Slice Subnet Management Function (T-NSSMF), which manages the transport network resources through the interface with the Transport Network controller in the orchestration layer. Together, these components enable end-to-end connectivity among network elements, ease the deployment of isolated services with performance guarantees, and yield an efficient use of network resources, by configuring and allocating slices according to specific use case requirements.

Given the importance of cross-border slice continuity, 5GMED introduces a design for network slice federation (Fig. 4). To trigger resource requests for federation, we propose using Slice Federation as a Service (SFaaS) [15], encapsulating such requests. This mechanism, driven by a Slice Federation Manager, translates 3GPP slice requirements to network slice federation needs, mapping user slice context to appropriate services. The host OP's Slice Federation Manager records the status of federated slices and manages a database. Various APIs

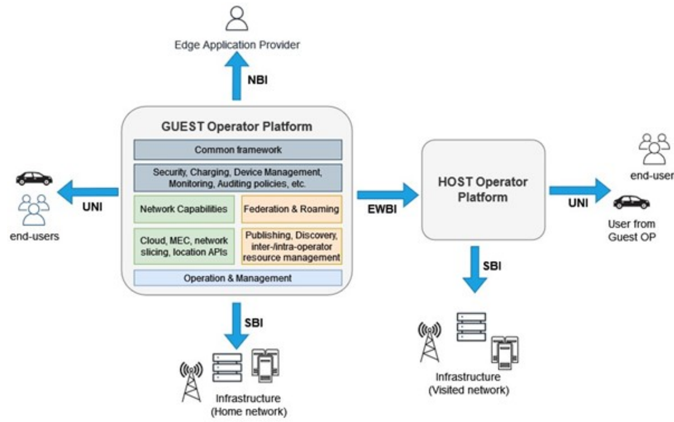

Fig. 3: Operator Platform concept and interfaces

(a) French segment.

(b) Spanish segment.

Fig. 2: Location of 5G sites in cross-border corridor.

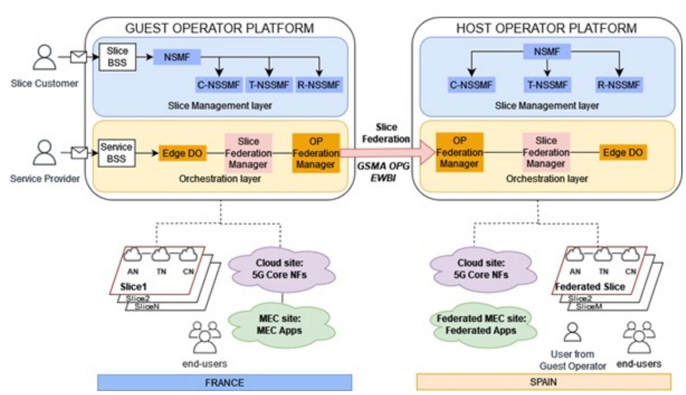

Fig. 4: Orchestration and slice federation based on Operator Platform concept

(e.g., slice-status request) must be included in the EWBI to inform the guest of successful slice federation and the next services to be federated.

Limitations in dynamic slicing implementation were found. First, it is challenging to dynamically adapt network slices to changing needs or traffic patterns. Moreover, the transport network's rigid and pre-defined network structure does not easily accommodate dynamic changes. In the absence of dynamic capabilities, the 5GMED implementation resorts to static RAN slicing, i.e. manual configuration of slice parameters directly in the gNodeB. Thus, cross-border mobility is not managed at the slice management level. The transport network uses static VLANs to isolate traffic among services and access networks. Integrating 5G Core as a service also implies a pre-defined for deploying any defined core slices.

VI. Lessons learnt

This section summarizes insights from the 5GMED cross-border network architecture [5] implementation and testing in the Castellolí test site and cross-border corridor. Initial tests focused on assessing roaming capabilities, particularly handovers between gNodeBs from Sunwave and Ericsson. Due to compatibility-related challenges, the Castellolí test site was reconfigured to exclusively use Sunwave gNodeBs. Current testing involves handovers between Ericsson's and Nokia's gNodeBs in the cross-border corridor, showing improved results due to their classification as Tier1 vendors commonly adopted by network operators, fostering better interoperability.

Roaming optimization poses another significant challenge. To tackle it effectively, we concentrated on testing these techniques at the Castellolí test site. This allowed the creation of numerous cross-border scenarios quickly, while replicating them in the cross-border corridor was more time-consuming. This decision streamlined the efforts of the project's network team, enabling them to learn and progress more efficiently. However, challenges remained due to the ongoing development of commercial 5G Cores for inter-PLMN handovers. Thus, the project had to align its timeline with the manufacturer's release roadmap and conduct additional tests with various 5G Core releases and their associated roaming techniques. For instance, increased delays in the release of the N14 interface further complicated handover implementation. We gained a clearer understanding of the roaming behaviour in movement when the correct 5G Core parameterization was found.

Another significant challenge arose from UE limitations. Most smartphones do not support testing with non-commercial PLMN-IDs, affecting the performance of end-to-end network trials. Additionally, only a restricted number of UE models support network slicing, often restricted to a single active slice. Some RAN vendors, such as Sunwave, lacked support for slicing within their equipment, making it infeasible to test slicing in the Castelloli small-scale test site, as planned. Implementing orchestrated (dynamic) network slicing on the 5G RAN side also remains a challenging task. While commercial RAN equipment does enable communication with an orchestrator via Operations Support Systems (OSS), integrating an OSS is not cost-effective for a project with few of gNodeBs. The idea of utilizing an existing OSS from Vodafone or Free Mobile was rejected due cybersecurity risks concerns.

Last, the complex terrain along the cross-border corridor complicated the transport network deployment. The intricate network design required multi-hop microwave links and multiple fiber interconnections, making the transmission a particularly challenging aspect in the commissioning of each node.

VII. Conclusions

This paper presented the 5GMED vision on how to deploy two 5G SA networks for the Mediterranean corridor cross-border between Spain and France. Furthermore, we have studied a challenging environment in the corridor that leads to the use of multiple technologies and heterogeneous networks. Moreover, we have identified four challenges related to cross-border scenarios, namely reducing latency and interruption time during roaming, in addition to cross-border orchestration and network slicing continuity. Finally, the network implementation adopted by 5GMED to overcome these challenges has been described with a focus on the cross-border challenges. Heavy test and trial campaigns are being carried out for performance evaluation of the network and use cases. The trial results are promising and will be presented in a future work.

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