Evaluation of 5G Train Neutral Host Architecture for Future 5G Railway Communications

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Abstract*—Providing 5G seamless and secure services for train passengers is very challenging. In addition to the challenges related to high-speed, many others, such as low signal quality due to 5G coverage holes, tunnels, and complex orography, may compromise the Quality of Service (QoS) provided to train passengers, especially in trains crossing international borders. To overcome these challenges, the EU-funded Horizon 2020 5GMED project has devised a cross-border 5G network architecture that allows train passengers to have the same QoS they have at home in whichever country they are. The network architecture is based on the concept of train neutral host, which operates as a service provider for other mobile network operators. The communication between the train and the ground is facilitated by a heterogeneous network infrastructure comprised of 5G StandAlone (SA), IEEE 802.11ad, and satellite networks to minimize the probability of having low quality signals along the rail track. The seamless switching between these network technologies is performed using Adaptive Communication System-Gateways (ACS-GW) developed in the project. In this paper, we propose the train neutral host architecture, and present the performance evaluation results obtained in a realistic environment over 5G SA networks deployed on the Mediterranean cross-border corridor between Spain and France. Experimental results show satisfying results in terms of service throughput, latency and train inter-cell handover.

***Index Terms*—5G, cross-border, mobility, seamless roaming, railway communications, neutral host.**

I. INTRODUCTION

The high Quality of Service (QoS) provided by 5G networks has paved the way to integrate new services and verticals such as Connected and Automated Mobility (CAM) and railway communications [1] [2]. In addition, 5G provides new key technologies such as network slicing that allows to divide the physical network into multiple isolated logical virtual networks with different resource allocations and guaranteed QoS to provide services to different verticals on-demand [3]. Another promising feature is the distributed User Plane Function (UPF) that allows the deployment of Multi-access Edge Computing (MEC) servers as close as possible to User Equipment (UE). As a result of these features, higher network performance can be achieved (e.g., lower latency and higher throughput) suitable for services such as digital twins [4], cooperative perception [5], and entertainment [6]. In this context, the EU-funded Horizon 2020 5GMED project has developed a network architecture optimized for CAM and railway communication in cross-border scenarios [7] [8]. The project aims at establishing a 5G network infrastructure with the goal of covering both sides of the Mediterranean cross-border corridor between Spain and France in a holistic manner while meeting strict performance requirements in terms of service end-to-end latency, data rates, reliability and service availability for CAM and railway use cases.

The question explored in this paper is how to improve the connectivity of train passengers. Today, there are two options available for passengers' connectivity: either connect to the on-board Wi-Fi when it is available or stay connected to the Public Land Mobile Network (PLMN) of the passenger's Mobile Network Operator (MNO). In the latter option, the passengers will frequently experience fast-changing, and often poor, Quality of Experience (QoE), due to the fact that usually national MNOs do not target covering rail tracks. Therefore, 5G coverage on rail tracks is often poor and the attenuation introduced by the train structure worsens the problem. The other option, Wi-Fi network on-board the train, helps to improve the QoE. It is based on a Wi-Fi router connected to a satellite link or even connected to several national MNOs, using external antennas on the train rooftop. In this way, the signal attenuation introduced by the train structure is avoided, and the diversity of MNOs that can be used improves the service as each MNO does not cover the rail track with the same QoS. However, the Wi-Fi solution has several drawbacks. The passengers have to take an action to connect to the Wi-Fi network, it is not as secure as a 5G, and some services may not be accessible. In addition, some segments of the rail track will have poor coverage, resulting in an overall poor Wi-Fi QoE.

Another alternative to offer better connectivity to train passengers is to deploy a train neutral host solution like the one proposed in the context of the 5GMED project using 5G technology [8]. The idea is to deploy several gNBs (i.e., 5G small cells) on-board of the train with a backhaul to a 5G core located on ground. When a passenger steps into the train, his/her UE will connect to the 5G small cell without any required actions. The backhauling of the gNBs on-board requires train-to-ground connectivity where multiple access networks can be combined to have a robust train access network, for which multi-connectivity solutions are required. 5GMED explores three possibilities for backhauling (5G, IEEE 802.11ad [9] [10] and satellite [11]), to which the backhaul data will be routed dynamically.

The contributions of this paper can be summarized as follows: *i)* the implementation of a new train neutral host solution to provide seamless connectivity to train passengers, *ii)* the development of a KPI collection tool to measure the service performance in real-time without impacting the overall network performance, and *iii)* the evaluation of the proposed solution on a real cross-border scenario over two 5G SA networks deployed by 5GMED in the Mediterranean corridor between Perpignan (France) and Figueras (Spain).

The remainder of this paper is organized as follows. In Section II, we present the architecture of the train neutral host solution. In Section III, we discuss how the proposed architecture facilitates seamless connectivity inside trains that move across international borders. In Section IV, we describe the measurement setup and test campaign, and we discuss the performance evaluation results. Finally, we provide concluding remarks and future work in Section V.

II. IMPLEMENTATION OF THE TRAIN NEUTRAL HOST ARCHITECTURE

The challenge investigated in this paper is the development of a train neutral host architecture to provide seamless connectivity to passengers inside trains. The idea is to deploy a Train Neutral Mobile Network (TNMN) on-board of the train together with a train-to-ground access network. In this section, we explain and discuss the different solutions.

A. Train Neutral Mobile Network

The TNMN can be implemented by deploying either a full 5G network, i.e., 5G Core and 5G Radio Access Network (RAN), or only a 5G RAN. This TNMN, which can be operated by the railway operator, will have bilateral roaming agreements with the PLMNs of different countries to provide seamless connectivity inside the train. To this end, two deployment options can be envisaged: RAN sharing using Multi-Operator Core Networks (MOCN), or train neutral host.

In the case of MOCN, the 5G small cell in the train will be shared by all the PLMNs that have an agreement with the operator of the TNMN and it will broadcast the PLMN-IDs of all these PLMNs inside the train. The UEs in the train will connect to the in-train 5G small cell transparently, as if it belongs to their own MNOs. All UEs' data and control planes will be forwarded to their corresponding PLMN cores, which will simplify signaling and billing mechanisms. The number of PLMNs sharing the 5G small cell is limited to fifteen, as specified in the parameter *PLMN-IdentityList3-r11* [12]. This should be sufficient if the train does not cross more than three countries. One major drawback of this approach is the configurations of the train 5G small cells, managed by the TNMN operator, to route all users packets to their corresponding PLMN core. This might have a negative impact on the provided QoS. Another drawback is that the 5G small cell is allowed by regulators to broadcast only the PLMN-IDs of the PLMNs that are active in the country. Otherwise, there could be violations of roaming agreements between MNOs.

In the case of the train neutral host, the passengers stepping into the train will roam from their home PLMN to the TNMN, and vice versa when stepping outside of the train. The Local Break-Out (LBO) roaming mechanism is more suitable in this case to reduce latency. The 5G small cell in the train will broadcast the PLMN-ID of the TNMN. The 5G Core network can be deployed on ground or in the train. In the first case, the ground 5G Core should have enough computational and storage resources to serve all train passengers. All data and control packets should be forwarded to this 5G Core. To reduce latency, a distributed UPF approach can be also an option. In the second case, the full 5G network (Core and RAN) should be deployed in the train. A small 5G Core instance that can serve a couple of hundreds of users can be sufficient in this case. Some products already have these integrated solutions as in the case of Amarisoft, a French equipment vendor [13]. In this case, standard IP packets will be sent from the train. The decision upon which solution to use depends mainly on the cost comparison between deploying very big 5G Core network or several small 5G Core instances. In addition, the small 5G Core option should support roaming to the local PLMNs via secure transport networks (e.g., IPX or SEPP), which can be difficult in practice. To guarantee the required QoS by each PLMN, the TNMN operator can provide a network slice in the 5G small cell for each PLMN with the required QoS.

In 5GMED, we adopted the train neutral host approach with a 5G Core network deployed on the ground as it is simpler and provides better QoS guarantees. We shall denote from now on the in-train 5G small cell by the neutral host gNB. The solution includes an Amarisoft gNB located inside the train (neutral host gNB) and a Free5GC core[1] [14] located on ground, as depicted in Fig. 1. In commercial trains, one 5G small cell will be deployed in each coach.

B. Train-to-Ground Access Network

Another challenge is the connection of the neutral host gNB to the ground 5G Core. Due to the coverage problem resulted from the environment crossed by the train, a special network infrastructure on-ground has been deployed by 5GMED to hide the complexity of the radio environment. This network infrastructure includes, in addition to 5G networks on-ground, other Radio Access Technologys (RATs) to provide service in the coverage holes of the 5G networks, in particular, 70 GHz IEEE 802.11ad [9] and satellite. The train-to-ground access network is illustrated in Fig. 1. It includes the following components:

1) *Adaptive Communication System-Gateways (ACS-GW)*: In order to isolate the UE from the complexity of the heterogeneous train-to-ground access network, a multi-connectivity gateway is used to switch between the different Radio Access Network (RAN) technologies in a transparent way. This gateway is represented in Fig. 1

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[1] FreeGC is an open-source 5G Core based on 3GPP Release 15.

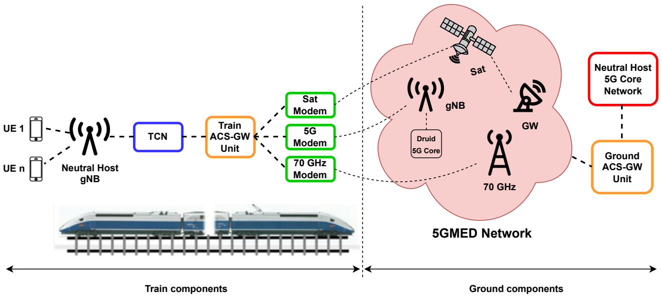

Fig. 1: Train neutral mobile network architecture.

as the ACS-GW unit [15], which is installed inside the train. In addition to the ACS-GW inside the train, there is a similar unit on the ground. A tunnel is created between the two ACS-GWs to hide the complexity of the train-to-ground connection. The ACS-GW enhances connectivity between train and ground networks using an adaptive packet forwarding strategy that ensures IP mobility and session continuity across various RAN. This system simplifies complex network handovers for train users with an IP/UDP tunnel overlay network for each RAN. In terms of functionalities, the ACS-GW acts as a middleware, linking the train's central switch to the RAN gateway, while remaining unnoticed by end devices on the train. It operates on a per-application basis, classifying processed flows based on configurable matching rules and identifying associated application IDs. Furthermore, the ACS-GW actively tracks application flow, collecting data on tunnel status and train position, which allows it to adjust the current RAN associated with applications when necessary. Another key feature is its Forwarding Orchestrator, which associates each application with a forwarding policy to determine the radio technology for packet transmission, altering the destination MAC address in packets to direct them to the correct RAN gateway. For IP mobility, the ACS-GW employs a tunneling overlay method using IP/UDP encapsulation, linking each RAN with an IP/UDP tunnel maintained through keep-alive messages exchanged between the ACS-GWs on the train and ground. These messages serve dual purposes: they check tunnel status and update Network Address Translation (NAT) bindings. The ACS-GW data plane is implemented as an extended Berkeley Packet Filter (eBPF) program, leveraging the eXpress Data Path (XDP) hook in the Linux kernel for optimal performance [16].

2) *Train Communication Network (TCN)*: The TCN enables communication among all the identified components on-board the train, including the ACS-GW, neutral host gNB and the three different RATs. Passengers UEs are not directly connected to the TCN. They will use the neutral host gNB to establish a connection. To achieve the maximum train-to-ground network performance, the TCN switches must provide Ethernet interfaces (ports) supporting up to 10 Gbps to connect the different on-board devices; otherwise, the TCN itself could be a bottleneck. For fulfilling these requirements, a single-mode optical fiber is deployed along the train.

3) *Train-to-ground connection*: As depicted in Fig. 1, three different radio access units are installed on board of the train: 3.5 GHz 5G NR, IEEE 802.11ad [9], and satellite. Each unit connects to its respective RAN endpoint that is part of the 5GMED network infrastructure before reaching the ground ACS-GW unit. For example, the 5G radio access unit connects the TNMN to the nearest ground gNB which then routes the packet to the ground ACS-GW through the 5G Core. The main features of the three radio access units are described below.

- *5G NR radio access unit*: The 3.5 GHz 5G NR radio access unit provides train to ground connectivity through the 5G network. The main devices required on the train are a 3.5 GHz antenna and a 5G modem. The antenna model installed on the train roof is a Huber+Suhner model 1399.17.0222 [17] that supports frequency bands from 617 to 960 MHz and 1350 to 7125 MHz. A Quectel RM500Q-GL 5G modem [18] is installed inside the train. From one side, the 5G modem will be connected to the TCN, and from the other side, it will be connected to the gNBs on the ground through the external antenna. To provide the 5G connectivity, the 5GMED project deployed two 5G SA networks, one in Spain and one in France, with six Ericsson gNBs in Spain and six Nokia gNBs in France, and two Druid 5G Cores [19] with distributed UPFs.
- *70 GHz radio access unit*: The network based on the 70 GHz IEEE 802.11ad technology provides high performance train-to-ground connectivity. The 70 GHz radio access units on-board the train are connected to the rail track side units. Each train contains two radio access units, located at the train head and the train tail. In a similar way, reverse and facing antennas are located on every rail track side pole. Train and ground units are connected via electronic self-directed beams between them. Each element on the train roof contains also two antennas pointing in opposite directions: the front unit is connected to the nearest pole in the direction in which the train is moving. Once the connection is made, the ground antennas will follow the train's movement, using advanced beam-forming techniques. The beam will continue to be aimed at the rear unit of the train as the train moves forward. The process continues through the successive poles along the track.
- *Satellite radio access unit*: The devices required on-board the train to provide satellite connectivity are one satellite antenna and one satellite modem. The satellite antenna installed on the roof of the train

is a reliable, low-profile, two-way antenna based on Gilat Raysat ER7000 [20], which is designed to handle challenging environmental conditions and extreme changes common in mobility applications. It enables real-time broadband satellite communications for video, voice and data for trains and large vehicles. The satellite modem is installed in a rack inside the train and connected to the TCN. The modem is a HT2500 modem from Hughes [21], with OpenAMIP v1.17 certified. The modem is connected to the ACS-GW unit through the TCN. As the deployment is done with a 3rd party the antenna has been supplied with an Antenna Control Unit (ACU). Finally, the satellite antenna on board of the train connects to a GEO satellite via HISPASAT satellite network, which is connected to a teleport ground station located in Arganda del Rey in Madrid (Spain). This Teleport is connected to the 5GMED network infrastructure, providing satellite connectivity along the trip where the train has line-of-sight with HISPASAT satellite. One of the biggest advantages of satellite communication is its ability to provide coverage worldwide. Satellite communications have historically been considered prohibitively expensive, but advances in technology have made them more affordable than ever. A single satellite can cover a larger area, significantly lowering the cost per coverage area, making satellites a cost-effective network mobility solution.

III. SEAMLESS ROAMING IN CROSS-BORDER SCENARIOS

The deployment of 5G small cells in closed and dynamic environments, such as trains, does not exempt from complying with the different radio regulations of the countries where the train is located. When crossing country borders, radio transmission regulations change in terms of transmission frequency, maximum transmission power and, in some cases, even Time Division Duplex (TDD) patterns. This means that the radio parameters of the small cells covering the train should change accordingly to maintain UEs' session without dropping.

When the border crossing event is detected (e.g., through positioning mechanism connected to the small cells on board), the small cells will autonomously change its configuration parameters using one of the two options described below:

- The same logical cell is used, but its configuration is changed dynamically. This option requires the availability of gNBs that can perform such dynamic configuration without disconnecting the cell, which can be challenging for existing solutions.
- Several cells will be logically created and each cell will be activated (i.e., transmit power increased from very low value to the maximum allowed). The two cells will be configured as neighbor cells to facilitate handover. The drawback of this method is that each cell will use a different frequency which will result in splitting the available bandwidth in the gNB between the different cells.

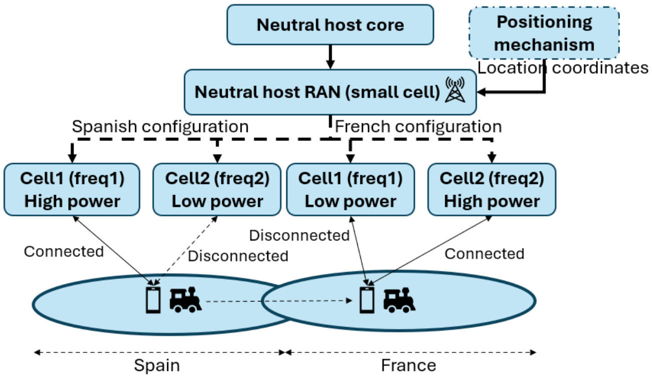

Fig. 2: Seamless cross border implementation.

The first solution might lead to session drops as there will be no handover between the two cells due to lack of signal measurement. Therefore, we adopted the second option and deployed an Amarisoft callbox classic [13] that serves two different cells using different frequencies. The frequency of each cell has been configured in line with the spectrum license obtained from the regulators of the two countries. As shown in Fig. 2, when the train approaches the border, the cell transmitting in Spain starts to decrease its transmitting power until it is off when the train crosses the border. Simultaneously, the cell operating in France starts to increase its power until reaching the maximum. This procedure will allow the UE to measure the signal of the second cell and report it to the network so that normal handover will be triggered at the border. It should be noted that this implies only a handover operation between two cells but and not roaming.

IV. PERFORMANCE EVALUATION RESULTS

In this section, we experimentally evaluate the performance of the train neutral host solution over three backhaul technologies: 5G, 70 GHz, and satellite. To this end, we first describe the system setup and the measurements campaigns that were conducted on the real cross-border scenario. Then, we define the service Key Performance Indicators (KPIs) measured during the experiment. Finally, we present and analyze numerical results for the different backhaul technologies.

A. *Setup of the Train Neutral Host System*

The Free5GC is deployed in two Virtual Machines (VMs) located in Castelloli (Spain). One VM runs the control plane functions and the other runs the UPF. Each VMs runs on an Ubuntu server Linux machine with 4 GB of RAM and 50 GB of storage. The ground ACS-GW is deployed on a Linux server machine located in Llers (Spain), where the train parking station is located. A microwave link is installed to connect the site in Castelloli with the site in Llers. The neutral host gNB located inside the train is parameterized to include two logical cells for transmitting at different frequencies as described in

Section III. The gNB's parameters are summarized in Table I. Finally, the UE consists of a generic laptop connected to a Quectel RM500Q-GL 5G modem [18], which enables the communication with the small cell, and a GPS receiver. The traffic is then generated from this laptop by requesting a YouTube video and a conference video call.

TABLE I: Neutral Host gNB parameters.

Parameter	Value
Cell 1 (Spanish) central freq	3936 MHz
Cell 2 (French) central freq	3960.540 MHz
Bandwidth	20 MHz
PLMN ID	00102
TDD pattern	7/2
Slice Differentiator (SD)	01
Slice/Service Type (SST)	0000

B. Measurements Campaign: Experiment Types

In order to evaluate the performance of the train neutral host architecture, we conducted two different types of experiments: *1)* on-board of a train that remains stationary in a fixed position, and *2)* on-board of a commercial van traversing the corridor and crossing the border between Spain and France on multiple times.

For the first type of experiment, we setup the train cellular network by deploying a 5G small cell inside the train where train users can connect to. This represents the neutral host gNB. Due to the unavailability of the 5G RAT at the time of executing the tests, performance tests over 5G backhaul are not performed and the train ACS-GW is configured to have the highest priority to satellite.

The second type of experiment is dedicated to test the backhaul over 5G technology using a commercial van. All the train network equipment, consisting of the neutral host gNB, TCN, train ACS-GW, and 5G radio access unit, were installed inside the van. These equipment are powered up using a set of batteries and a power inverter. The 5G radio access unit establishes a connection with the closest gNB of the 5G SA network of 5GMED on ground, which routes the traffic to the ground ACS-GW through the Druid 5G Core. Two sets of measurements are collected: static and dynamic measurements.

The static measurements are collected with the van parked close to a ground Ericsson gNB near Pont de Molins (Spain). The exact coordinates are (42.336996, 2.919526 in longitude and latitude, respectively).

The dynamic measurements are collected with the van moving from La Jonquera (Spain) to Le Perthus (France). The aim of the dynamic measurements is to evaluate the impact of the frequency change of the neutral host gNB on the network performance. When the van reaches the French border, the neutral host gNB detects the event through the GPS receiver and switches its frequency using a specific Python script.

C. Definition of Key Performance Indicators

In order to evaluate the performance of the train neutral host architecture, a measurement toolkit has been developed in Python to measure service KPIs: throughput and latency. In the following, we describe how these two metrics are measured. The results are then stored on a local MongoDB database.

1) *Throughput*: the throughput is measured at the UPF of the 5G neutral core network and it is measured in uplink and downlink separately. Using the Linux kernel network interface statistics, we retrieve the amount of packets sent and received on the GTP-U interface. In this way, we measure the uplink and downlink service throughput.
2) *Latency*: the latency is measured between the UPF of the 5G core network and the neutral host gNB. It is measured in uplink and downlink separately. Using Scapy module from Python, we sniff GTP-U packets (on UDP port 2152) from both ends. A transmit timestamp is first added to each sniffed packet at the source and destination. Then, the tool inserts the packet ID, timestamp, IP source and destination in the database. If the packet ID already exists in the database, the tool updates it by inserting a new timestamp representing the received time of the packet. The latency is then calculated as the difference between the timestamps. We finally differentiate between uplink and downlink latency based on the source and destination addresses.

D. Experimental Results

The results of the service performance over the network with 5G, 70 GHz and satellite backhaul in the train and in the van stationed in a fixed position are depicted in Fig. 3 to 6. The results of uplink and downlink throughput are depicted in Fig. 3 for 5G backhaul and Fig. 4 for 70 GHz and satellite backhaul. In all the tests, a YouTube video was requested. Since video packets are not downloaded continuously over the Internet, we first observe bursts of throughput representing the time at which requested packets were being downloaded from the YouTube server over the internet. In Fig. 3, we can see that the highest downlink throughput was over 18 Mbps for 5G backhaul. Similarly in Fig. 4, we observe a maximal downlink throughput for the satellite (70 GHz, resp.)reaching a value of slightly lower than 6 Mbps (10 Mbps, resp.). It should be noted here that these values reflect the service bandwidth consumption and not the full network capacity at the time of the tests. For instance, a bandwidth capacity test was performed with iperf3 (a linux IP networks measurement tool) over the satellite, and it resulted in a peak downlink throughput reaching 100 Mbps. The values however, vary depending on the environment conditions and the weather forecast.

The results of latency are depicted in Fig. 5 for 5G backhaul and in Fig. 6 for 70 GHz and satellite backhaul. In Fig. 6, we clearly observe the high latency resulted from backhauling over the GEO satellite of around 320 ms in both uplink and downlink directions, while IEEE 802.11ad scores the lowest

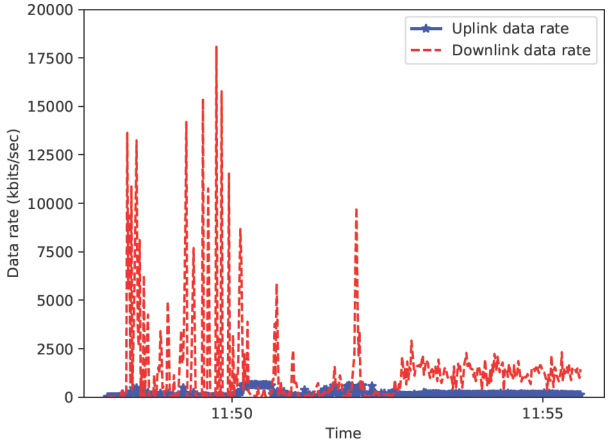

Fig. 3: Service throughput in the van over 5G backhaul in static scenario.

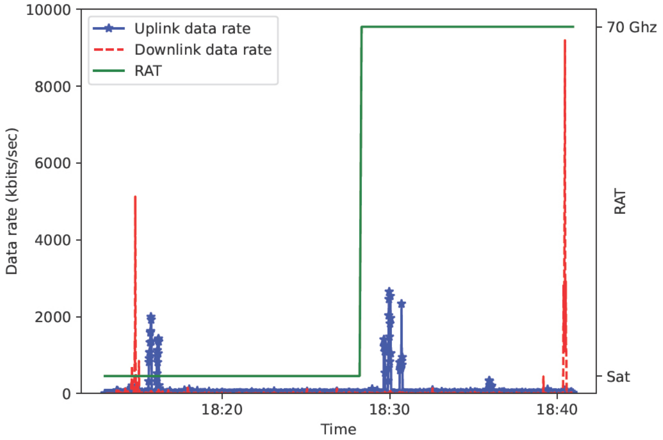

Fig. 4: Service throughput in the train over satellite and 70 GHz backhaul in static scenario.

latency varying between 2 and 10 ms. The results of the static measurements are summarized in Table II for the uplink (UL) and downlink (DL) max data rates and average (Avg) latencies.

In Fig. 7 and Fig. 8, we present the results of latency and throughput, respectively, obtained in dynamic measurements with the van moving from La Jonquera (Spain) to Le Perthus (France), connected to the 5G SA networks of 5GMED. The aim is to evaluate the impact of the frequency change of the neutral host gNB when crossing the border. In Fig. 7, we can observe an impact on the uplink latency that goes up to 210 ms at the time of the frequency switch. This is due to the roaming process experienced by the 5G radio access unit. The figures show also that there is no interruption time during the inter-cell handover, which will lead to a seamless handover inside the train when crossing the borders.

V. CONCLUSION

In this paper, we presented the EU-funded Horizon 2020 5GMED project vision on how to provide seamless and secure 5G services for train passengers. We have discussed different technical solutions, and we explained the approach adopted by the 5GMED project, which is based on a train neutral host architecture that provides the 5G services to train passengers as if they are doing national roaming. The proposed architecture is evaluated in the Mediterranean cross-border corridor between Figures (Spain) and Le Perthus (France). In addition, a python-based passive tool was developed to measure the different KPIs and the results were satisfied in terms of throughput, latency, and seamless inter-cell handover inside the train.

As future work and as anticipated in the 5GMED project, we plan to study the robustness of the proposed solution by evaluating it in a high speed train moving between Spain and France with several user terminals. Moreover, we plan

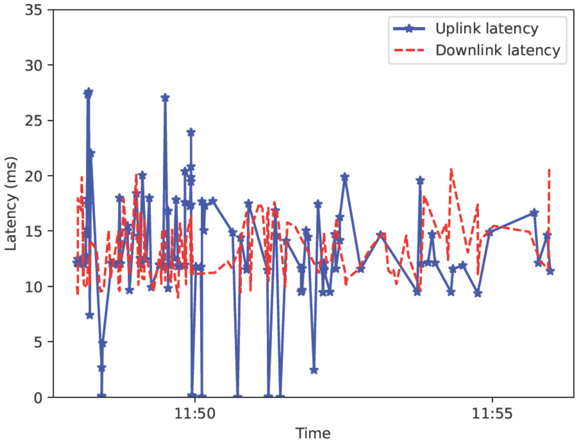

Fig. 5: Service latency in the van over 5G backhaul.

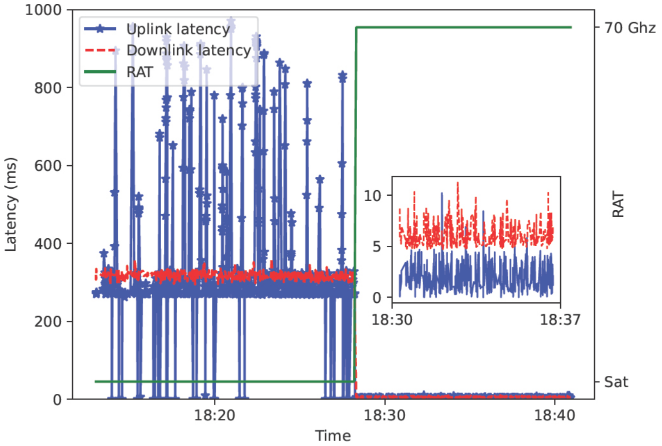

Fig. 6: Service latency in the train over satellite and 70 GHz backhaul in static scenario.

TABLE II: Summary of results from static measurements.

RAT	Max DL Data Rate	Max UL Data Rate	Avg DL Latency	Avg UL Latency
5G	18 Mbits/sec	650 Kbits/sec	13.3 ms	14.1 ms
Satellite	5.1 Mbits/sec	2 Mbits/sec	317 ms	356 ms
70 GHz	9.1 Mbits/sec	2.65 Mbits/sec	6 ms	1.88 ms

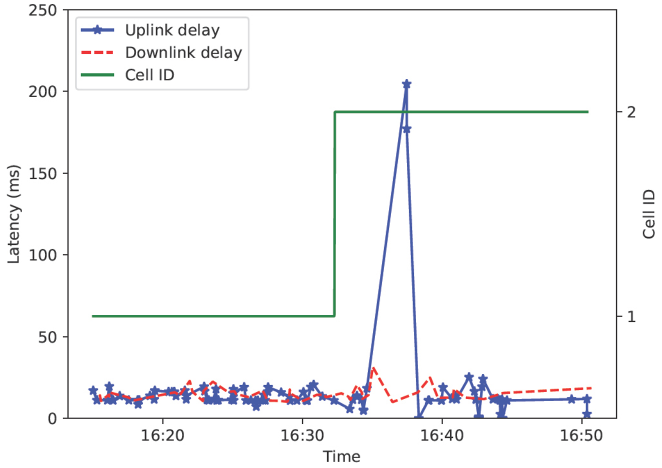

Fig. 7: Service latency in the van over 5G backhaul with switching cells.

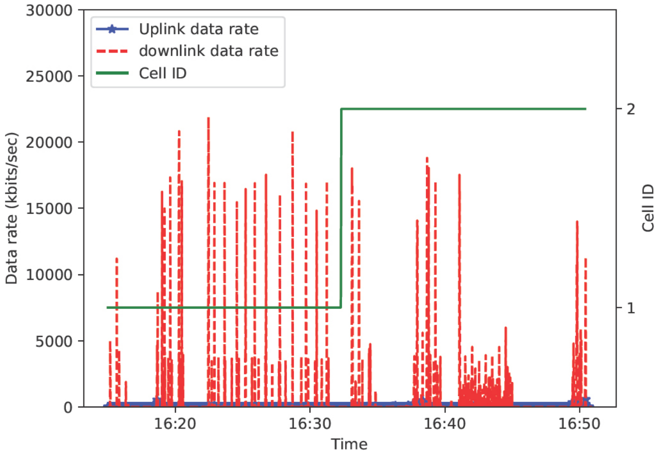

Fig. 8: Service throughput in the van over 5G backhaul with switching cells.

to evaluate the proposed architecture when Local-Breakout roaming is implemented at the border to compare the impact of roaming type of the performance inside the train. Finally, we aim at integrating non 5G backhaul links, such as the satellite and 70 GHz links, with the 5G network in order to ensure the continuity of the 5G slice over non 5G transport links. To this end, we will integrate the slice classifier component described in [22] to preserve the 5G slice continuity over the non 5G transport links (i.e., 70 GHz and satellite).

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