5GMED Seamless Connectivity for Digital Trains

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Abstract— The communication services of future trains require hyperconnectivity between trains and track. Future Railway Mobile Communication System (FRMCS) reserved bands will not be able to cover all digital train requirements including passengers' services. The 5GMED project adopts the idea where Infrastructure Managers (IMs) will collaborate with Railway Undertaking (RU) to facilitate the connectivity to Mobile Network Operator (MNO) communication services and vice versa (complemented with the use of satellite networks), with an architecture open to build new business models and relationships between stakeholders. This approach encompasses an adaptative Gigabit train-to-track connectivity solution able to fit Digital Train requirements. The 5GMED project will demonstrate these capabilities through four representative services deployed on a TGV of SNCF (French Train Operator) in a challenging scenario: a cross-border section of the Mediterranean corridor between Figueres (Spain) and Perpignan (France).

Keywords— Digital Train, Gigabit-Train, FRMCS, 5G SA, IM-MNO collaboration, 70GHz, ACS-GW, satellite

I. Introduction

As GSM-R, the traditional radio system for railways, approaches obsolescence, the International Union of Railways (UIC) is specifying its successor, the Future Railway Mobile Communication System (FRMCS) [1], to address railway's needs for train operation. These needs include services such as the control command and signalling on-board and trackside subsystems: European Train Control System (ETCS), Automatic Train Operation (ATO), and Connected Driver Advisory System (C-DAS). There is another set of applications like Train Control Monitoring System (TCMS), Passenger Information System (PIS), and emergency communications between train cabins and control centre. Both groups will be progressively integrated into FRMCS. These FRMCS services can be provided by networks that use dedicated spectrum. The European Commission (EC) has decided on the harmonized use of the paired frequency bands 874.4 - 880 MHz and 919.4 - 925 MHz and of the frequency band 1900-1910 MHz for Railway Mobile Radio (RMR) [2].

Two additional important challenges must be faced that cannot be solved with this dedicated spectrum: *1)* the foundation for the digitalization of train operation will result in the need of additional bandwidth for new services: critical and non-critical video transmission, including the transmission of critical LiDAR and radar sensor data, is expected to become necessary for higher levels of railway automation. Similar requirement derives from staff services: browsing, mobile office, video conferencing, and the use of Augmented Reality/Virtual Reality or simultaneous audio translation; and *2)* services oriented to passengers: in the digital train vision, passengers will be entertained or work in trains as if they were at home or in the office. The passenger shall have excellent coverage from mobile operators and will have access to Over-The-Top (OTT) services such as collaborative videoconferences, high-resolution content, gaming, dynamic travel information, and targeted advertising. The average demand for Internet connectivity per passenger is expected to be around 1 Mbps by 2025, making necessary a connectivity between 0.7 and 1 Mbps per passenger, i.e., between 700 Mbps and 1 Gbps for trains with 1000 passengers [3][4][5], with growth based most likely on video on demand and cloud computing. This will lead to the Gigabit Train concept.

We assume that the case where Mobile Network Operators (MNOs) will provide this connectivity to the Railway Undertakings (RUs) is not the most probable scenario, as it means that MNOs will have to provide infrastructures far from densely populated areas, which have low return of investment. On the other side, RUs would like to avoid active equipment as Wi-Fi access points because it adds CAPEX and OPEX they aim to reduce. In this context, we describe in this paper the approach used in 5GMED to solve these issues. 5GMED project, supported by the Horizon 2020 research and innovation programme of the European Commission, aims to assess the potential of 5G technologies (3GPP Rel.16) in fulfilling the requirements of Cooperative Awareness Message (CAM) and FRMCS applications in cross-border situations.

This paper is organized as follows. In Section II, we present the 5GMED approach and architecture. In Section III, we describe the services to be demonstrated in a railway use case. In Section IV, we discuss the different technologies used to provide connectivity to trains. In Section V, we draw the conclusions and discuss future works.

II. 5GMED Approach

Several services (described in Section III) will be demonstrated in the track segment of the Mediterranean corridor between Figueres (Spain) and Perpignan (France), which is managed by LFP [6], in two different trains: an LFP maintenance train (maximum speed 90 km/h) and an SNCF's TGV (speed about 300 km/h). The goal is to demonstrate these services working with seamless connectivity in a cross-border situation. The border is located at one side of the 8.3 km length tunnel of Le Perthus. To do this, two virtual train to track networks are being deployed over the same infrastructure, sharing common resources: one is dedicated to railway services, and the second one is to provide passengers services. Both networks use a common 10 Gbps train backbone, running in parallel to the in-service train network used for critical services. In addition, the 5GMED project is designing and deploying a train to track multi-connectivity solution encompassing different radio access technologies: 5G Stand Alone (SA) network, IEEE 802.11ad 70 GHz network, and Satellite connection.

The multi-connectivity solution is deployed as the network infrastructure layer of the architecture proposed in [7]. This architecture (shown in Figure 1) also includes the following layers: MEC layer, orchestration layer, slice management layer, cloud layer, and data analytics layer. The description of these layers is out of the scope of this paper and can be found in [7].

III. 5GMED Services

A. *FRMCS P1 Service: Advanced Sensors Monitoring on-board*

The first service is representative of an actual use case for train operators. Today, train operators are doing regular maintenances and verifications on their train based on the mileage of the train or time interval. This is called preventive maintenance. Stopping a train for verification or maintenance is very time-consuming, costly, and sometime unnecessary. Therefore, train operators are increasingly looking at predictive maintenance.

Predictive maintenance is a concept where a large amount of sensors data is analysed to predict if a system is likely to fail in the near future. There are multiple ways to the sensors data (e.g., specialized software, AI models, etc.), but they all need regular and frequent data from many sensors. These sensors are already present in today trains, but their data are directly analysed on-site through specialized algorithms. For example, if the difference between 2 speed sensors is above a specific criterion, a message is sent to the ground to inform the train operator of the issue.

To improve the actual analysis methods, the use of AI models is considered. However, training the AI models requires a continuous flow of sensors data. If the AI models are on the ground, a low latency and reliable connection between the train and the ground is needed. This is what will be tested in 5GMED.

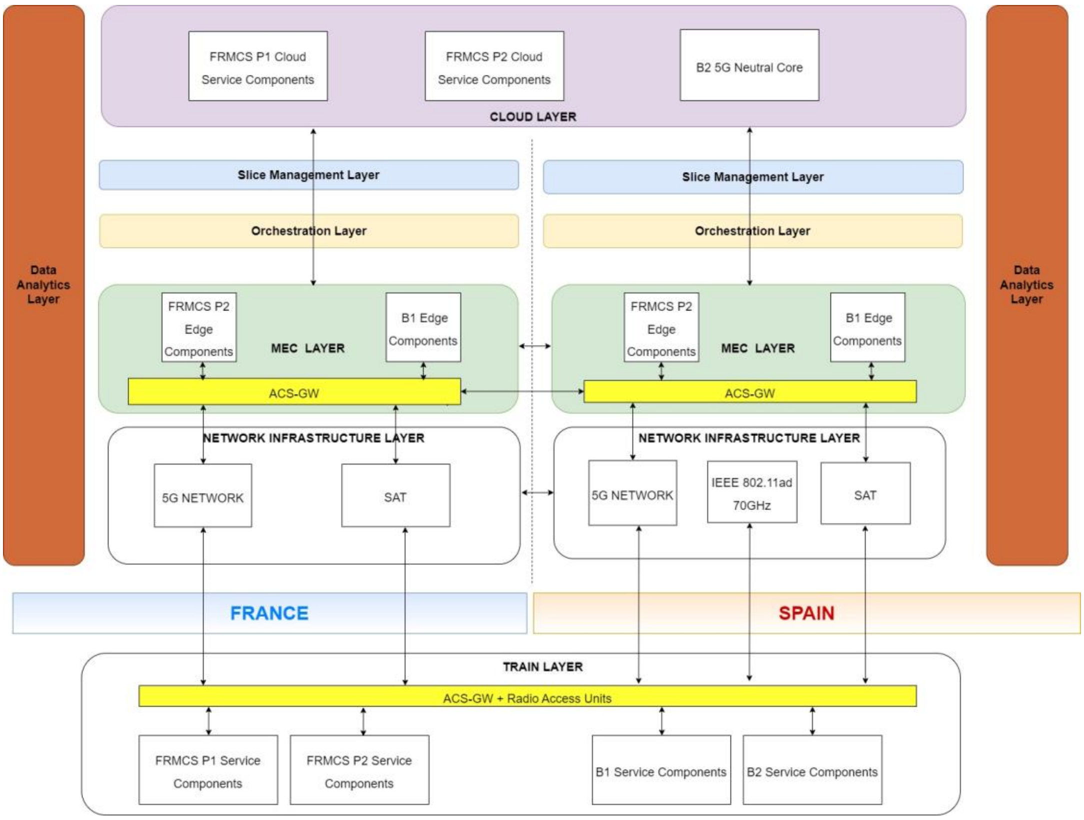

Figure 1 - 5GMED Architecture for Railways

B. FRMCS P2 Service: Railway safety – Obstacle Track Detection

The role of this service is to provide a representative Edge computing application for future remote detection-based systems like autonomous vehicle or obstacle detection. Specifically used for that type of applications, LiDAR sensors can measure surrounding geometric 3D information and store 3D data in a structure called cloud of points, which can be processed afterwards. This technology has been exponentially improved in the last decades and can nowadays capture huge amount of data per second thanks to low-latency and high-bandwidth wireless networks.

In the 5GMED project, we present an Edge computing AI-based obstacle detection system that uses LiDAR data captures of a train surrounding. The LiDAR is placed in the train cabin and scans the front tracks and environment. The data are then sent to an Edge server that processes the incoming raw data in two steps: 1) a Simultaneous Localization and Mapping (SLAM) algorithm computes the current frame geo-localization; and 2) an AI algorithm processes the aggregated geo-localized point clouds to detect potential obstacles, e.g., car or pedestrian on or near the tracks. The schematic of the proposed edge-computing system is represented in Figure 2: (1) a LiDAR captures the train surrounding and data is sent to an Edge server, which (2) processes the data, (3) shows aggregated point clouds of the train surrounding tainted with false colours according to point height, and (4) sends warning to the local train operator if an obstacle is detected.

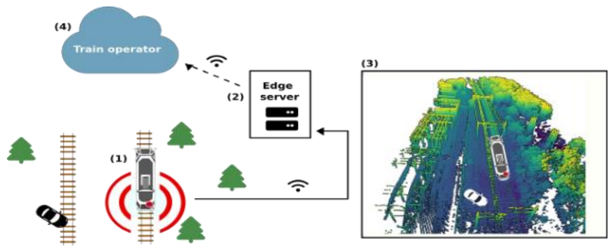

Figure 2 - Obstacle track detection

C. B1 Service: High Quality Wi-Fi for Passengers

The aim of this service is to provide high quality internet connection to the big number of train passengers. There are two basic challenges under the scope of the B1 service. The first challenge is to provide a high-quality Internet access to a train full of passengers, which is done using several Wi-Fi 6 access points [8] that are distributed inside the train vehicles (to improve the performance of the Wi-Fi signal received by the passengers' user equipment inside each vehicle). The second challenge of the B1 service is to demonstrate the Gigabit Train concept. The network that provides connectivity between the train and the ground, so called Train Access Network (TAN), must be able to support the amount of traffic equivalent to a train full of passengers. Once the traffic reaches the ground, it can be delivered to an aggregation point in which a high-speed Internet connection can be provided. The above solution is of little value if the quality of the connection is significatively below what passengers would experience as if they were at home. To assure the quality of the connection, traffic generators are used to simulate a train full of passengers using this service, and measure its main KPIs: interruption time, upload/download throughput, one-way latencies, jitter, and packet loss, which are targeted with values similar to enterprise connections.

D. B2 Service: Multi-tenant Mobile Service for Passengers

Today's world train passengers have two options to connect their smart phones: direct connections to their MNO or connection to Wi-Fi access points on board the train when available. In the first option, passengers will usually face fast-changing Quality of Experience (QoE), which is often poor. This is because most MNOs do not directly target train tracks' coverage, leading to poor coverage in general and because the signal is weakened due to penetration losses through the train metallic structure. The in-train Wi-Fi solution helps improving user experience avoiding this type of problems. The train Wi-Fi access points are connected to the ground using either a satellite link, which is expensive for train companies, or a Wi-Fi router connected to all available national MNOs with improvement of QoE by means of an external antenna on the train rooftop and by the diversity provided by connectivity with all MNOs. However, this solution has two main drawbacks: the passenger must take an action to connect to the Wi-Fi and this connection is not as secure as 5G network. Also, many areas will have poor coverage from all MNOs. Therefore, the 5GMED project proposes to test a neutral train MNO to solve these problems by providing train indoor 5G coverage with an on-board 5G small cell connected to a Distributed Antenna System (DAS) that covers all the train coaches.

The aim of B2 service is to explore the rollout of such a neutral train MNO for a highspeed train. The neutral train MNO will use an on-board 5G small cell, which will be backhauled through the TAN, i.e., train to ground access network, to a 5G-Core on ground. In that way, the passengers will have a high-quality 5G access to the train MNO services through their own devices, secured and without any action required from them. This assumes an existing TAN with performance meeting the onboarded gNB backhauling requirements in terms of throughput and latency. The TAN is typically a multi-connectivity network, including 5G and satellite. The B2 service, will evaluate the video conference and video streaming on a high-speed train of SNCF.

Two options were considered for B2:

- The passengers' MNO deploys its own 5G slices on the neutral train MNO, and therefore, the traffic generated by its subscribers in the train will be backhauled to its own 5G-Core.
- The passengers' MNO contracts roaming agreements with the neutral train MNO. When stepping into the train, the passenger UE will roam from its MNO to the neutral train MNO, and vice versa, when stepping outside the train. This is the option explored in 5GMED.

In this architecture, we face two important challenges for implementing service B2 in 5GMED:

- The satellite link used for the TAN will not be 3GPP compliant. This puts the challenge of maintaining the 5G slicing through the backhauling on the satellite link. This is solved by using a component named "slice classifier" developed in 5GMED and modifying the Session Management Function (SMF) in the 5G-Core.

- In the cross-border scenario of 5GMED, the spectrum allocation will be different in each country and the frequencies used by the 5G small cells in the train will have to be changed when crossing the border between France and Spain. A specific component developed in 5GMED will solve this challenge. This component consists of having two active cells with two frequencies, where one has very low power and the second has the nominal power. The two cells are considered as neighbours so that the UE scan both frequencies. When crossing the border, the developed component will detect the change and swap the power of the cells so that the UE connects to the right frequency of the country.

The use of the satellite link in B2 service for backhauling is rendered even more attractive by the recent availability of Low Earth Orbit (LEO) satellite constellations operators, which propose latency performances far better than the one offered by the GEO satellites operators. Therefore, substantial portion of railway tracks connectivity could be addressed using LEP satellites, which can be use for completing the 5G or side link access for the TAN.

IV. 5GMED Connectivity

Railway tracks are often deployed in environments with irregular orography, vast zones with dense vegetation, and tunnels. In such diversified environment, radio communications will face many challenges that require the usage of a heterogenous network where different technologies can be appropriate for different environmental challenges. Therefore, the 5GMED approach is to use three technologies covering the whole railway track: 5G SA network, IEEE 802.11ad at 70 GHz, and Satellite.

To have a seamless handover between these different technologies, the 5GMED project has developed a gateway that selects the best access technology used by each individual service. It reacts automatically to all kind of changes in the coverage of the different access network that composes the TAN. For this reason, the gateway is named Adaptive Communication System-Gateway (ACS-GW).

A. 5G Stand-Alone (SA) Networks

Two 5G SA networks have been deployed along the Spanish-French border. The 5G networks are used as the main networks and aim at providing seamless connectivity especially at cross-border area and to provide a network slice for the train network. It includes the following mobile subnetworks:

- Radio Access Network (RAN) consisting of six Ericsson gNodeBs (gNBs) in the Spanish side and six Nokia gNBs in the French side. The gNBs operates at frequency bands N77 and N78 and allow testing handover between different frequency bands. As the railways go through a tunnel at the border, a Distributed Antenna System (DAS) will be deployed inside the tunnel.

- 5G Core networks deployed using the Raemis product from Druid [9].

By using the 5G SA networks, we can satisfy the requirements of the services, in terms of high data rate and low latency, and more importantly seamless connectivity across the border with low mobility interruption time. The seamless connectivity is provided with the support of:

Figure 3- 802.11ad 70 GHz access network

- Home Routed Roaming (HRR) and Local Breakout roaming (LBO) with N14 interface activated between Access and Mobility Management Functions (AMFs). The N14 interface allows the AMF in the Visited Public Land Mobile Network (VPLMN) to get the UE context from the source AMF, thus reducing the registration time. The N14 interface also reduces the user plane reestablishment time, as the VPLMN is informed of Home PLMN User Plane Function (UPF) and UE IP address. In addition, the two 5G SA networks are declared as equivalent PLMNs to eliminate the need for blind attachment attempts.

- Radio optimization by declaring the cells at the border as neighbour cells to reduce the scanning time.

Furthermore, the 5GMED project adopted a neutral host approach at the borders and in the French side by reusing RAN infrastructure through Multi-Operator Core Network (MOCN) concept. At cross-border, MOCN enables radio optimization in the roaming process by allowing the configuration of additional radio parameters (i.e., neighbours cells information). On the French side, it reduces the infrastructure CAPEX and OPEX needed to deploy the TAN by sharing the gNBs of other MNOs.

The 5G NR connectivity in the train will be provided by Quectel RM500Q-GL 5G modem connected to a GNSS/MIMO 2x2 cellular antenna Huber+Suhner 1399.99.0130.

B. IEEE 802.11ad at 70 GHz

This radio access technology, specifically oriented to the track to train communication, uses the licensed exempt operation in the 57-71 GHz millimetre wave band to supply a gigabit capacity. The standard used to connect the train to track units is IEEE 802.11ad with infrastructure extensions [10]. The trackside units set up the radio link with beamforming to approaching trains. This link establishment process is extremely short, around 2-3 seconds. This technology will supply approximately 17 km of high-bandwidth coverage from the entrance/exit of the Le Perthus tunnel towards the LFP Maintenance Base in Llers, close to Figueres.

The track to train architecture is based on a series of trackside antenna units deployed on poles attached to the existing catenary stanchions along the track. Each trackside unit has one forward and one reverse facing antennas which will set up a radio connection with antenna units deployed on both train ends, as it is shown in Figure 3.

Typically, trackside units must be deployed each kilometre. A backhaul to interconnect the trackside units is based on a single sixteen multicore optical fibre. The multicore fibre ends at the LFP Llers maintenance base, on a 24-ports Ethernet switch. Finally, a central switching point in the same site, consisting in a L2 switch, an aggregation unit (two flows are received from the train, from the rear and front antennae) and a firewall (the data is encrypted), complete the access network. At this point, the network is connected to the common backhaul of the 5GMED network.

Two major features must be highlighted: the low power consumption of the units, less than 40 watts; and the fast deployment of the network, three months, including fibre, power, and poles installation.

C. Satellite

Several areas of the Perpignan-Figueres corridor have irregular orography and are rural areas with even dense vegetation. This makes the terrestrial cellular coverage challenging and satellite connection an ideal complementary candidate for the 5G network deployment in 5GMED. Therefore, satellite is a solution explored to provide connectivity in the coverage holes of the terrestrial radio access networks.

A low-profile two-way satellite antenna is deployed on the train roof and will be connected to an onboard satellite modem to provide train to track connectivity.

Additionally, the project will test how 5G coverage can be extended to remote areas where the telecom infrastructure is loose. For this purpose, gNBs will be backhauled with the help of a very small aperture terminal (VSAT) providing satellite connectivity.

D. Adaptive Communication System-Gateway

The ACS-GW [11] was developed specifically for the railway scenario of 5GMED to grant connectivity between the train and the ground networks. It provides an adaptive multi-connectivity packet forwarding strategy, ensuring IP mobility and session continuity through the available radio access technologies. More simply, the ACS-GW allows end-users on the train to communicate with devices on the ground (and vice versa), masking the complexity of handover between Radio Access Networks (RANs) through an overlay network consisting of an IP/UDP tunnel for each of the RANs. The 5GMED project developed this solution instead of standardized solutions such as Access Traffic Steering/Switching/Splitting [12] as the latter requires that the non-trusted systems and the equipment connected to them support the standardized interfaces, which is not the case in what exists in the market, especially in terms of existing UEs, whereas the ASC-GW is transparent to the user; therefore, any user that enters the train should be able to get access whatever the UE he/she uses.

The equivalent of ACS-GW for standard FRMCS services is the FRMCS Gateway. As the support of critical services is not part of the 5GMED project, performance FRMCS services provided to RUs and services provided to the passengers are not integrated using the FRMCS framework. Instead, the ACS-GW uses a practical plug and play approach to integrate a service in the communication system based in traffic classification based on the headers of the service data packets. The main difference in the requirements of the different systems is: while the FRMCS-GW relies on their reliability and security aspects (because is related to critical services), the ACS-GW requires high performance (packet inspection, classification and packet forwarding at 10 Gbps), flexibility in terms of service integration, and interaction between gateways to locate the trains in the different tracks.

The ACS-GW deployment comprises one device on board the train and one or more on the ground, functioning as mobile anchors. The main functionalities of the ACS-GW consist of the following:

- Transparent Aggregation: the end devices in the train are unaware of the ACS-GW, which is connected to the train central switch and acts as a middleware box between the routers and the RANs gateway.
- Flow Classifications: the ACS-GW works on a per-application basis, so it classifies the processed flows according to configurable matching rules and returns the associated application ID.
- Flow Tracking: the ACS-GW tracks the active application flow and collects information on tunnel status and train position. Based on this information, the ACS-GW, if necessary, modifies the current RAN associated with the applications.
- Forwarding Orchestrator: each application identified by an application ID is associated with a forwarding policy that defines the radio technology for transmitting the packets. The ACS-GW modifies the destination MAC address in the original packets to forward them to the correct RAN gateway.
- IP Mobility: the ACS-GW uses a tunnelling overlay approach based on IP/UDP encapsulation [9]. Each RAN is associated with an IP/UDP tunnel established and periodically updated by exchanging keep-alive messages from the ACS-GW on the train to the ACS-GW on the ground. The keep-alive messages have a dual purpose, to verify the tunnel's status and to update the Network Address Translation (NAT) binding between the two ACS-GWs. The direction of the flow defines the behaviour of the ACS-GW. In particular, the ACS-GW that starts a new flow decides its classification, and the other ACS-GW learns this classification.
- Flow Dispatcher: the ACS-GW encapsulates and forwards packets to the external RANs gateway according to the application ID retrieved in the classification block.

The ACS-GW is an extended Berkeley Packet Filter (eBPF) [13] program that can be attached to different hooks in the Linux kernel, specifically the ACS-GW exploits the eXpress Data Path (XDP) hook in the earliest networking driver stage to ensure excellent performance.

V. CONCLUSION

A huge additional bandwidth and network resources are needed to fit the requirements of the two groups of services that Digital Train vision addresses (FRMCS performance services and Passengers services). New business models, sharing infrastructure networks between MNOs and IM/RUs, are in the critical path to obtain significative results in this area. The Multi-Edge Computing (MEC) layer must be also considered under the scope of these multi-stakeholder networks.

To satisfy these needs, railway networks (including internal train networks) must scale up to 1 Gbps. The communication system to provide this type of connectivity needs to satisfy some main features: 1) Railway mobile radio must be prepared to support different types of radio access technologies; 2) in all scenarios, the capability to select the radio technology used per service is essential (main and back-up preferred access, automatic seamless handovers between different radio access technologies); and 3) this shared networks must be designed with quality parameters similar to the fixed networks designed to satisfy needs of business and/or residential areas.

The requirements for critical services and Digital train services differs in terms of scale, security requirements and type of deployment approach (FRMCS service registration methodology vs plug-and-play used in 5GMED, FRMCS gateway requirements versus ACS-GW requirements). Therefore, the convenience to have separate or common communication systems (or the interaction between them) must be carefully analysed in future projects.

Finally, the possibility that IM/RUs resell bandwidth to MNOs or a neutral operator to provide passenger services based in the Gigabit Train capabilities can be expanded to new business/operational models that allow the railway operators to host the active components (i.e., Wi-Fi AP's, DAS, or on-board cells), that can be directly managed by the MNO as part of their own network(s) with the use of 5G slices or similar mechanisms.

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