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D5.1 Railways Application Requirement Analysis Report

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Synopsis	This report analyses the services definitions of UC3 (railways performance and business services) and presents the requirements and the initial design to support the test cases of UC3 in the railway scenario. It provides a functional and behavioural description of the use case. In addition, the report provides an overview of the main elements of the railway communications system, including the Train Communication Network (TCN) and Train Access Network (TAN),

	describes the management of the handover between the 5G, 70 GHz and satellite technologies, and summarises the main cross-border issues in the railways scenario.
List of Keywords	5G, Architecture, requirements, service components, train infrastructure

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Acronyms and Abbreviations

5G	Fifth generation
5GC	5G Core
5G SA	5G Stand Alone
ACS	Adaptive Communication System
ACS-GW	ACS-Gateway
AI	Artificial Intelligence
AP	Access Point
ARFCN	Absolute Radio Frequency Channel Number
BPF	Berkeley Packet Filter
CCTV	Closed-Circuit Television
DSNG	Digital Satellite News Gathering
DU	Distributed Unit
eBPF	Extended BPF
EU	European Union
FPAs	Flat Panels Antenna
GA	Grant Agreement
GHz	Giga Hertz
gNodeB	A 3GPP-compliant implementation of the 5GNR base station
GNSS	Global Navigation Satellite System
HTTP	Hyper-Text Transfer Protocol
IMS	IP Multimedia Subsystem
IP	Internet Protocol
K_a band	Portion of the electromagnetic spectrum in the range 26.5–40GHz frequencies
KPI	Key Performance Indicator
KVM	Kernel Based Virtual Machines
LAN	Local Area Network
LiDAR	Laser imaging Detection and Ranging
MEC	Multi-access Edge Computing
mmWave	Millimetre Wave, the portion of the electromagnetic spectrum from 30 to 300 GHz
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
NAT	Network Address Translation
NVF	Network Functions Virtualization
NPU	Network Processor Unit
NR	New Radio
NUC	Next Unit Computing
OS	Operating System
PAT	Port Address Translation
PC	Personal Computer
PCIe	Peripheral Component Interconnect express
PLMN	Public Land Mobile Network
PLMN-ID	PLMN Identifier
QoS	Quality of Service
RAM	Random Access Memory

RAN	Radio Access Network
RAT	Radio Access Technology
RTSP	Real Time Streaming Protocol
SATCOM	Satellite communication
SIM	Subscriber Identification Module
TAN	Train Access Network
TCN	Train Communication Network
TCP	Transmission Control Protocol
UC	Use Case
UDP	User Datagram Protocol
UE	User Equipment
UPF	User Plan Function
VLAN	Virtual Local Area Network
VLAN-ID	VLAN identifier
VM	Virtual machine
WP	Work Package
XDP	eXpress Data Path

Executive Summary

This deliverable provides an analysis of the D2.1 services definitions document (Definition of 5GMED Use Cases [1]) for the railway use cases in order to derive the necessary requirements for the service components development process.

Based on the functional block mapping between the railway use cases and the 5GMED network architecture presented in D2.1 [1], this document provides an overall description of the different services components building blocks and requirements. These requirements are included in the form of tables in the specific sections describing the services functional blocks.

In a similar way, this document provides a description of the different communication components building blocks and requirements. These requirements are also included in form of tables in their corresponding sections. After that, two areas are highlighted: a detailed description of the features to be implemented in the components responsible for the selection of suitable wireless access technology, according to the heterogeneous coverage of the corridors (named ACS-GW units) and the expected effects of a set of identified cross-border issues: roaming, vertical handovers, and the existence of two different MNOs (Mobile Network Operators), and railway administrator companies at each side of the border.

1 Introduction

1.1 Purpose of this document

The main objective of this document is to analyse the definition of the 5GMED use cases that must be deployed in the railway scenario, identify their requirements, and provide an initial design description to support the test cases derived from these use cases. The 5GMED use cases are defined in deliverable D2.1 [1]. The use cases that must be demonstrated in the railway scenario are:

a. **Railway performance and business services continuity** (Use Case 3 - UC3), in which several performance services together with business services for train passengers [2] will be provided while ensuring the service continuity in a high-speed train throughout the entire corridor. The definition of UC3 services is included in Section 4.3 of D2.1 [1].

b. **Follow-me Infotainment** (Use Case 4 - UC4), in which train passengers will be able to access media-based Infotainment activities (e.g., access to high quality media contents) while ensuring the service continuity in a high-speed train throughout the entire corridor. The definition of UC4 services is included in Section 4.4 of D2.1 [1]. This UC4 is not specific to the railways scenario but covers both transport modes in the cross-border corridor: automotive and railway. However, as the full UC4 will be showcased on the highway, only a subset of UC4 services will be demonstrated in the railway scenario with the UEs on-board the train directly connected to the 5G SA networks.

UC3 will be developed and tested in the context of WP5 for the railway scenario. Additionally, UC4 will be developed and tested in the context of WP4 for the automotive scenario (for details see D4.1 [3] Section 2.2.3, Section 3.4, and Section 4.3). Therefore, the description of the functionalities and requirements for the UC4 functional blocks is out of the scope of this document because it has already been provided in section 4.3 of D4.1. This document focuses on UC3.

1.2 Methodology

Firstly, based on the definitions of the railway use case and the high-level functional architecture presented in deliverable D2.1, we identify the functional blocks of UC3, and the main communication blocks required in the railway environment. The functional blocks include the functions related to one or more of the UC3 services defined in D2.1. The communications blocks are all those elements that provide connectivity between the service blocks on-board the train and the ones on ground.

Secondly, we present the components inside the functional blocks of each use case, as well as the relationship and interfaces among them. The design of the functional blocks is organized into a functional view and a behavioural view, which provide a coherent and complete description of the block components mapped into the 5GMED network architecture. The functional view shows the functional blocks split into their different internal components, describing the basic functionality of each component. The behavioural view shows how the different components of each functional block interact with each other, and the sequence of actions performed to implement the required functionalities of the UC service.

Thirdly, we provide a list of requirements obtained from the description of each service defined in D2.1. These requirements are presented together with the components of the functional design blocks. Finally, a similar procedure is applied for the communication blocks.

1.3 Structure of the document

The rest of this document is organized as follows. Section 2 shows the high-level functional architecture of UC3, which was presented in D2.1, including the functional blocks of the use case mapped into the different layers of the high-level 5GMED network architecture.

Section **¡Error! No se encuentra el origen de la referencia.** describes the functional blocks and service components of each UC3 service. Also, this section provides a set of tables identifying the requirements from the analysis of the use case definitions and describing the basic procedures the service components must satisfy. A specific subsection of each service is devoted to describing the cross-border behaviour of the service.

Section 4 presents an overview of the communication components, explaining their behaviour and capabilities. In addition, a set of tables identifying requirements is provided in an analogous way as in Section 3. Section 4 is completed with a special focus on the behaviour relative to two types of particular events: vertical handovers (explaining how the handover between multiple radio access technologies is handled) and the specific cross-border behaviour.

Finally, Section 5 concludes the document.

2 Use Cases High-Level Functional Architecture

UC3 provides four different services classified as performance and business services. These services were defined in D2.1 and are listed below:

- **UC3 Performance Services:**
    - **P1 service**: Advanced Sensor Monitoring on Board.
    - **P2 service**: Railway Track Safety - Obstacle Detection.

- **UC3 Business Services:**
    - **B1 service:** High Quality Wi-Fi to passengers.
    - **B2 service:** Multi-tenant Mobile Service.

Figure 1**¡Error! No se encuentra el origen de la referencia.** depicts the high-level functional architecture of UC3, which includes the functional blocks of the use case mapped on the different layers of the high-level 5GMED network architecture for cross-border scenarios that was introduced in D2.1 [1].

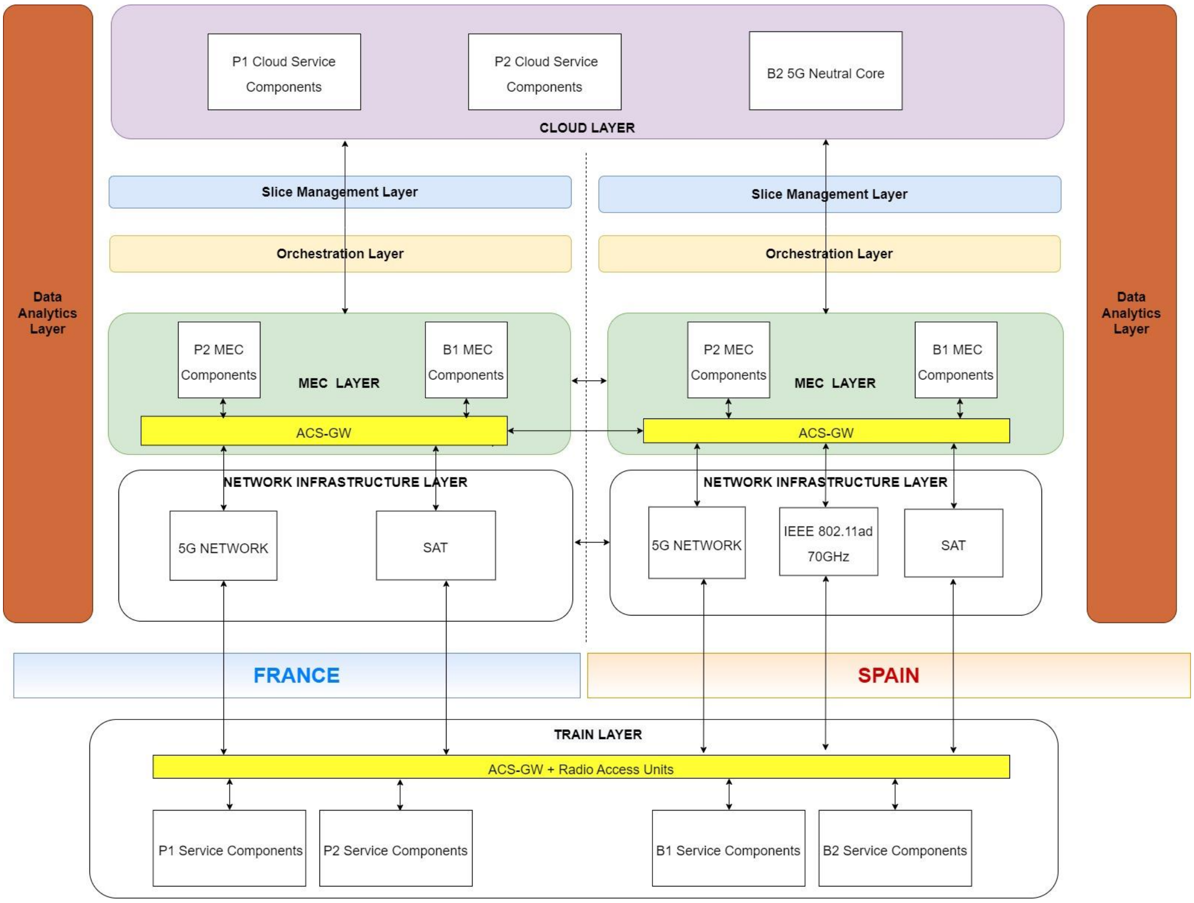

Figure 1 – High-level functional architecture of UC3 in the railway scenario.

As it can be observed in Figure 1**¡Error! No se encuentra el origen de la referencia.**, the functional blocks (in white colour) of UC3 in the railway scenario are included in three different layers: train, MEC layer, and cloud layer. These layers are briefly described below and the rest of the layers of the 5GMED network architecture are described in D2.1[1] and D3.3[8].

- The **train** is composed of all the components on-board the train: hardware infrastructure elements (i.e., servers, switches, LiDAR) and software functional blocks (i.e., service components deployed on the on-board infrastructure). The train contains:
    - Two functional blocks with all the components for the P1 service and P2 service of UC3.
    - Two functional blocks for the B1 and B2 services of UC3.
- The **MEC Layer** is devoted to host functional blocks that need to be close to the service components on-board the train for multiple reasons (such as to reduce latency, distribute a function for scalability or cost reasons, and separate administration domains). It consists of Virtual Machines (VMs) used to allocate instances of the different functional blocks and other infrastructure blocks dedicated servers (as the ACS-GWs, as example). One MEC will be available in each country, and the two MECs will be connected through a cross-border interface explained in Section **¡Error! No se encuentra el origen de la referencia.**. Each MEC

contains two functional blocks with the MEC service components for the P2 service and B1 service of UC3.

- The **Cloud Layer** is devoted to host the following functional blocks of UC3.
    - Two functional blocks that include the Cloud service components of the P1 service and P2 service of UC3. These blocks are part of a Train Control Centre.
    - One Neutral 5G Core for the B2 application of UC3.

As it can be observed in Figure 1, the network infrastructure layer facilitates the connectivity between the train and the functional blocks of UC3 in the MEC and Cloud layers. In addition, there are two Adaptive Communication System-Gateways (ACS-GW), in yellow colour, that operate as interfaces between the train and the MEC layers functional blocks. The operation of the ACS-GW is described in Section 4.2.1. The detailed description of the network infrastructure layer is included in deliverable D3.2 [7] and D3.3 [8].

3 Use Cases Initial Design and Requirements

This section provides a high-level description of the functional blocks that compose each use case service, their requirements, and the relevant interfaces between the components of each functional block.

3.1 UC3 Functional Blocks and Components

This section describes the functional blocks of UC3. For the sake of simplicity, the description is based on simplified block diagrams that only include the 5GMED network architecture layers where the functional blocks are allocated, and only one country is represented in the block diagrams.

Each functional block of UC3 is composed of several service components included in the corresponding layer to satisfy a function related with a particular UC3 service. Section 3.1.1 and Section 3.1.2 describe the components of the performance services and business services, respectively.

3.1.1 Performance Services

This section describes the components of the performance services in the train, MEC layer, and Cloud layer as shown in Figure 1. All these service components are depicted in Figure 2.

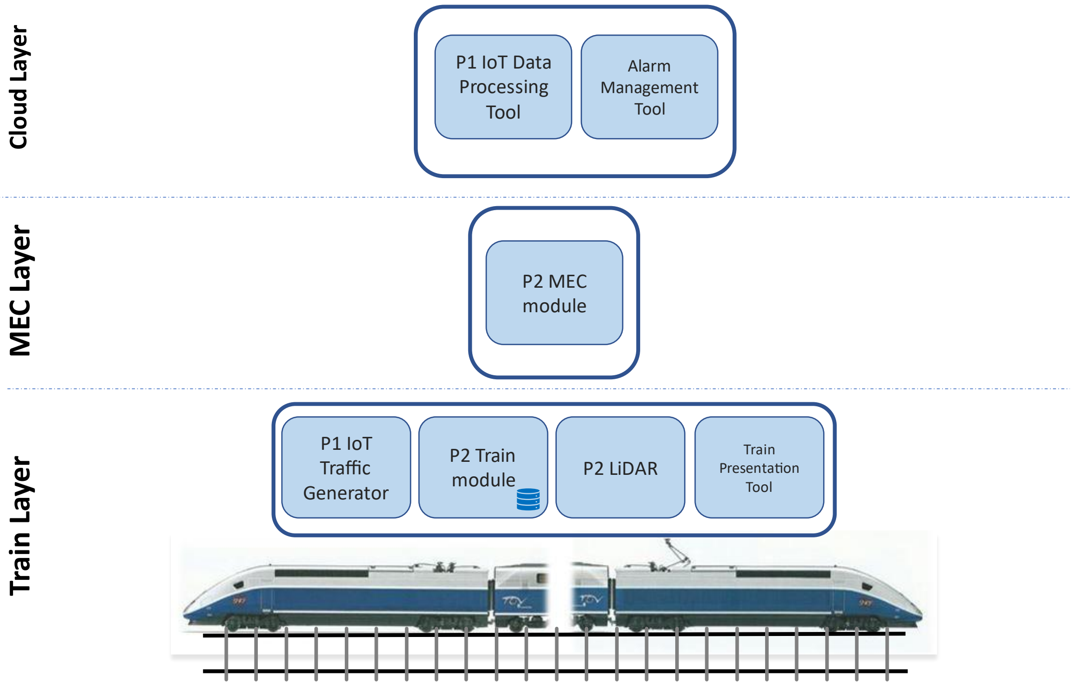

Figure 2 – UC3 Performance Services components

3.1.1.1 Train components

The components of the performance services of UC3 to be installed on-board the train are the following:

- The **P1 IoT Traffic Generator**: The Advanced Sensor Monitoring on Board consists in simulating a high number of sensors inside the train with an IoT Traffic Generator. The train **P1 IoT Traffic Generator** is the main responsible for generating the IoT traffic that will be sent to the cloud **P1 IoT Data Processing Tool**.

- The **P2 LiDAR:** This component is a commercial LiDAR (Laser imaging Detection And Ranging) device, intended to capture 3D point clouds of the railway scene, and more precisely of the adjacent railway tracks. The LiDAR data are forwarded to the **P2 Ground Module**.

- The **P2 Ground Module**: A small software module responsible for receiving LiDAR data and retransmitting them to the **P2 MEC Module**. It permits to remotely control the LiDAR parameters (e.g., speed, motor activation). This is needed because the LiDAR, as a sensor, does not provide server functionalities.

- The **Train Presentation Tool:** This service component is responsible for showing the messages and warnings received from the **Cloud Alarm Management Tool** on the train screen to alert the train staff. It is also responsible of collecting IoT data from the cloud **P1 IoT Data Processing Tool** and giving access to a web interface in order to show the sensor variations.

3.1.1.2 MEC Layer components

The components of the performance services of UC3 allocated at the MEC layer are the following:

- The **P2 Edge module**: It is responsible for processing the data sent by the **P2 Ground Module**. It contains the main system intelligence by centralizing all the computational processing algorithms in one place with appropriate hardware. It is composed by several submodules, including one for data orchestration and one for SLAM (Simultaneous Localization and Mapping) geolocalization.

3.1.1.3 Cloud Layer components

The Cloud layer components of the business services of UC3 simulate a simplified version of a Train Control Centre. The components of the performance services allocated at the Cloud layer are the following:

- The **P1 IoT Data Processing Tool**: It is responsible for receiving IoT data from the train **P1 IoT Traffic Generator** and sending data to the **Train Presentation Tool** showing sensor variations.
- The **Alarm Management Tool**: It communicates with the **P2 Edge Module** to raise alarms in case a potential obstacle is detected.

3.1.2 Business Services

This section describes the components of the business services at the train, MEC layer, and Cloud layer as shown in Figure 1. All the service components are depicted in Figure 3.

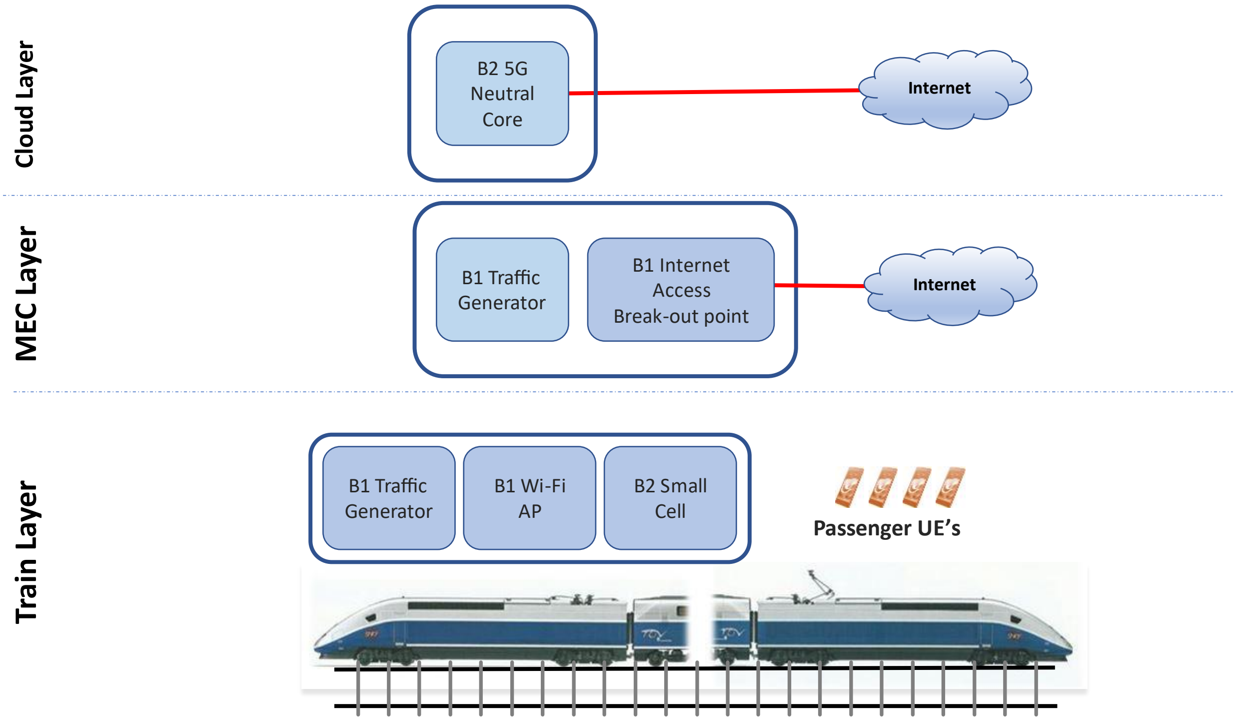

Figure 3 – UC3 Business Services components

3.1.2.1 Train components

The components of the business services of UC3 to be installed on-board the train are the following:

- A **B1 Wi-Fi Access Point:** This will allow the passengers access to the Internet.

- A **B1 Traffic Generator**: It is used to simulate the Gigabit Train concept [4]. It will be able to generate the aggregated traffic corresponding to a train plenty of passengers.
- A **B2 Small Cell**: A gNodeB will allow the passengers the use of mobile services in a similar way if they were provided from their own MNO.
- **Passengers' UEs**: (smartphones, tablets, or laptops) connected to the neutral host cell or Wi-Fi AP depending on the testcase.

3.1.2.2 MEC layer components

The components of the business services of UC3 allocated at the MEC layer are the following:

- A **B1 Traffic Generator**: It is used to send and receive the simulated traffic from/to the train.
- A **B1 Internet Access Break-out:** This component is a router that support NAT/PAT features in order to translate the multiple private IP numbering plans to IP public addresses and serve as traffic aggregation point for the Internet Access traffic of the train passengers.

3.1.2.3 Cloud layer components

The components of the business services of UC3 allocated at the Cloud layer are the following:

- A **B2 5G Neutral Core**: It is used to backhaul small-cells distributed in the train vehicles (for testing purposes, only one small-cell will be used)
- The B2 Internet Access Break-out function is included in the B2 5G Neutral Core functions.

3.2 UC3 Behavioural Views and Requirements

This section details the interaction between the components in each service of UC3. To show the interaction among the different components, the next subsections provide a behavioural view diagram for each of the five services of the UC3 defined in D2.1. For the sake of simplicity, the behavioural view diagram only includes the 5GMED network architecture layers where the service components are allocated, and only one country is represented in the diagrams.

Each subsection contains a specific subsection to explain whether or not the service needs to use the cross-border interface between the MEC layers in both countries. If so, the information to be exchanged among the edge service components is described.

Finally, this section presents the analysis of requirements to support the test cases in the form of tables.

The tables of the requirements comprehend the following information:

- ID, following the structure of R-AA-XXX; being AA an acronym for the service to which the requirements apply, and XXX an incremental number.
- Functional Block(s) affected: shows the functional block(s) object of the requirement.
- Description: brief explanation of the requirement.
- Importance: shows the necessity for the requirements following the MoSCoW notation (i.e., Must, Should, Could, Won't) [5].

Table 1 lists the requirements common to all UC3 services, but the specific requirements for each individual service will be presented in the following subsections. Common cross-border requirements are marked with an asterisk.

ID	Functional Block(s) affected	Requirement description	Importance
R-UC3-001 *	All	The service shall be provided with continuity, without disruptions, even in the cross-border scenario.	Must
R-UC3-002	All	The train service components must be isolated from the critical vehicle infrastructure systems.	Must
R-UC3-003	All	All the train and ground service components should be able to configure the MTU and the IP addresses via a Cloud DHCP server to facilitate the configuration	Must
R-UC3-004	All	All the components must be able to be configured remotely.	Must
R-UC3-005	All	All the components must be able to obtain the date and time reference from an external NTP server. This requirement is necessary in order to correlate events between components (i.e.: a failure and a variation in a service KPI)	Must
R-UC3-006	All	It is preferable to install EN50155 [6] compliant devices, but it is not mandatory. EN50155 specify the requirements of the electronic devices in rolling stocks (i.e.: tolerance to vibrations, temperature, interferences, moisture)	Could
R-UC3-007	3.5 GHz 5G NR modem	5GMED MNO SIM card available	Must

Table 1 - UC3 common service requirements.

3.2.1 P1 Service: Advanced Sensor Monitoring on Board

3.2.1.1 Behavioural View

Figure 4 represents the behavioural view of the P1 Advance Sensor Monitoring on Board. Each successive step is represented by an encircled sequential number.

The **P1 IoT traffic generator** on board generates the IoT traffic corresponding to 4000 sensors inside the train[2]. This data will be sent to the cloud layer every 100 ms ①. Moreover, an IoT sensor simulator inside this module specifically simulates two sensors on board, with predefined variations (square and

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[2] This is the maximum number of sensors that fits in an UDP packet using the format established by SNCF to identify a sensor and its value inside the packet.

sine wave shapes). The data from the sensors is received by the **P1 IoT Data Processing Tool** in the Cloud, which sends the IoT data to the **Train Presentation Tool** ②.

Finally, the **Train Presentation Tool** ③, installed on board of the train, shows the sensors variations. It also shows some statistics about the communication link. It requests these data from the **P1 IoT Data Processing Tool** in the Cloud. This allows testing the downlink and uplink communication channels.

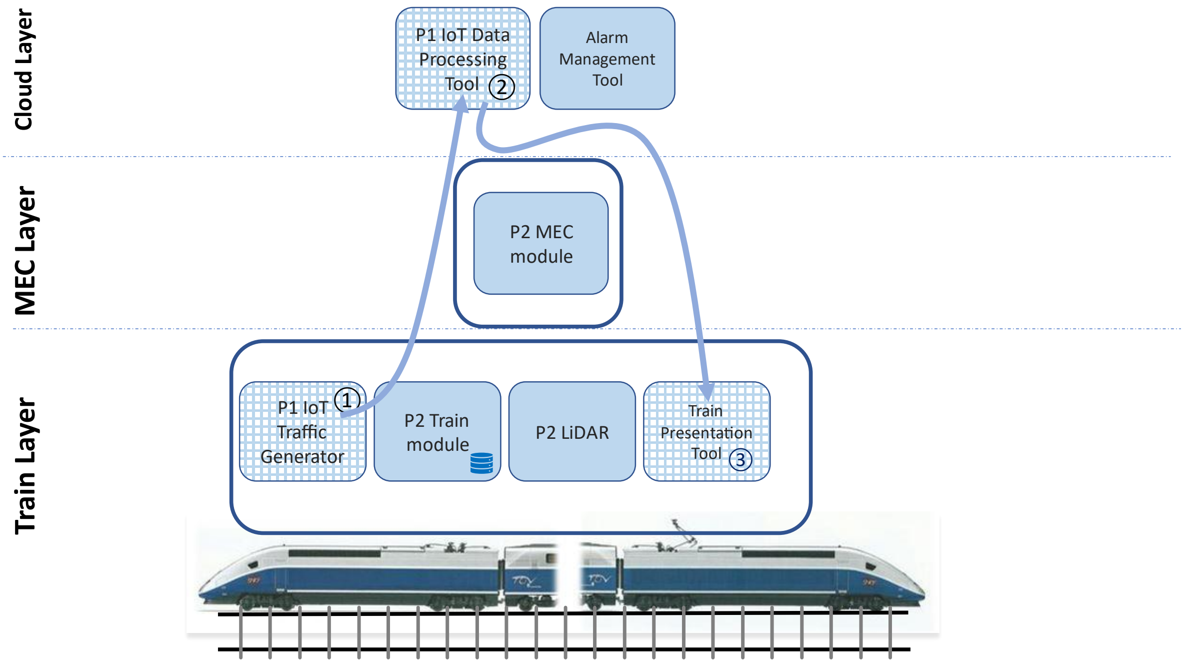

Figure 4 - Behavioural view for P1 Advance Sensor Monitoring on Board

3.2.1.2 Cross-border behaviour

Service P1 is cloud oriented. No specific cross-border issues must be addressed. It can tolerate the additional latency and interruption time that will be induced by the use of roaming at the border in the range defined by these P1 service KPI's.

3.2.1.3 Requirements

Table 2 shows the list of the P1 service components requirements.

ID	Functional Blocks affected	Requirement description	Importance
R-P1-001	P1 IoT Traffic Generator	Simulate 4000 sensor variables inside the train.	Must
R-P1-002	P1 IoT Traffic Generator	Send the IoT traffic corresponding to these 4000 variables every 100 ms to the P1 IoT Data Processing Tool.	Must
R-P1-003	Train Presentation tool	Registers to a ground server hosted by the IoT Data processing tool. The Train Presentation Tool uses MQTT to	Must

		receive the data from P1 IoT Processing Tool, which is a MQTT broker. So, in order to effectively receive data, the Train Presentation Tool subscribe (or register itself) to some topics.	
R-P1-004	P1 IoT Data Processing Tool	Receive IoT data from the P1 IoT Traffic Generator to be available on a screen inside the Train Presentation Tool	Must
R-P1-005	Train Presentation tool	Display P1 defined IoT data variations (square and sine wave shapes) on a web interface	Must
R-P1-006	Train Presentation tool	Display statistics about P1 downlink communication	Should

Table 2 - P1 service components requirements.

3.2.2 P2 Railway Track Safety – Obstacle Detection

3.2.2.1 Behavioural View

Figure 5 represents the behavioural view of the P2 Railway Track Safety – Obstacle Detection. In this service, a **LiDAR** will continuously take measurements of the train surroundings ①. The stream of data will be captured by an on-board computer, the **P2 Train module** ②, which will forward the data flow to the **P2 MEC module** in an MEC-layer server ③.

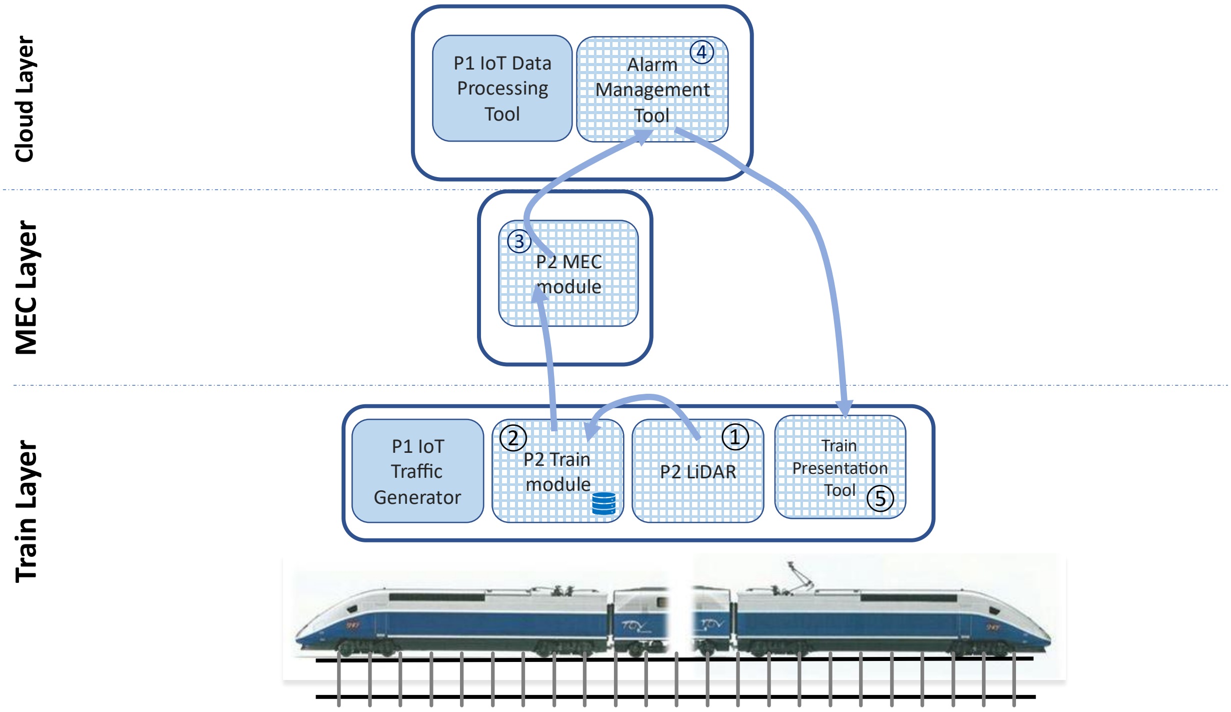

Figure 5 – Behavioural view for P2 Railway Track Safety – Obstacle detection.

In case that **P2 MEC module** detects an obstacle (as AI features were removed from the service, this alarm will be triggered manually), a warning with obstacle information will be sent to the **Alarm Management Tool** in the Cloud Layer ④. This warning will be forwarded to the **Train Presentation Tool** in the train ⑤. Figure 5 presents an overview of this P2 service pipeline.

3.2.2.2 Cross-border behaviour

There are two instances of the P2 MEC module, one in each country. The P2 Train module select the P2 MEC module to forward the LiDAR stream of data based in the train position (obtained from the Geolocation Module defined in section 4.1.2). Each P2 MEC module continuously suppress data after a certain amount of time, but relevant information is extracted from the processed data as specific features (e.g., type and frequency of obstacle encountered). When the train is crossing the border between the two countries, the LiDAR data stream is redirected to the corresponding new P2 MEC module by adjusting the data recipient address. At this point, an information sharing between edges could improve obstacle predictions by considering the extracted features of the previous AI module. This will require the deployment of cross-border interface between the two MECs. A theoretical approach based on Exposure Gateway platform is presented in D3.3 [8] but will not be deployed in 5GMED. Instead of this, a simplified direct exchange of information between the two P2 MEC Modules will be developed.

P2 can tolerate the additional latency and interruption time that will be induced by the use of roaming at the border in the range defined by these P2 service KPI's.

3.2.2.3 Requirements

Table 3 shows the list of the P2 service components requirements. Cross-border requirements are marked with an asterisk.

ID	Functional Blocks affected	Requirement description	Importance
R-P2-001	P2 LiDAR	Continuously capture 3D point clouds of the train environment, that is, the railway scene and the adjacent railway tracks. For the LiDAR, the frequency required is 10 rotation per second in dual-return mode (which is more-precise than single mode-return)	Must
R-P2-002	P2 LiDAR	Send data flow to the Train P2 Edge module. 20 Mb/s with a frequency of 753 packets per second for 10 rotation per second in dual-return mode.	Must
R-P2-003	P2 Train Module	Receive P2 LiDAR raw data and retransmit it to the P2 Edge Module.	Must
R-P2-004	P2 Train Module	Relay LiDAR parameter commands (e.g., speed, motor activation) for LiDAR remote control.	Must

R-P2-005 *	P2 Train Module	At cross-border event, this component redirects the data flow to the corresponding new P2 Edge module in the MEC layer by adjusting the data recipient address using train position.	Must
R-P2-006	P2 Edge Module	Process received data sent by P2 Train Module with a SLAM algorithm and make obstacle detection prediction at real-time.	Must
R-P2-007 *	P2 Edge Module	At cross-border event, an information sharing is made between Edge servers in order to improve obstacle prediction.	Must
R-P2-008	P2 Edge Module	Provide obstacle information to the Alarm Management Tool in the Cloud Layer when an obstacle is detected.	Must
R-P2-009	P2 Edge Module	Detect various type of obstacles on tracks and close to the tracks (e.g., trees, persons, vehicles).	Must
R-P2-010	P2 Edge Module	Provide the location of the track obstacle.	Must
R-P2-011	Alarm Management Tool	Process the obstacle warning coming from the P2 Edge Module	Must
R-P2-012	Alarm Management Tool	Transmit the obstacle warning to the Train Presentation Tool	Must
R-P2-013	Train Presentation Tool	Present to the train staff the obstacle warning with designation of the track where the obstacle is.	Must

Table 3 - P2 service components requirements

3.2.3 B1 High Quality Wi-Fi for Passengers

The B1 service is defined in UC3 with the following objectives:

1. To provide Internet access to the train passengers
2. To demonstrate the Gigabit Train concept [4]: how to provide access to a high-quality big pipe between the train and the ground.

A common practice to provide Internet access to the train passengers is collecting all the traffic generated by their UEs via Wi-Fi. A number of Wi-Fi APs are distributed inside the train vehicles, depending on the number of passengers. The traffic generated/received from/to the Wi-Fi APs is aggregated across the train to obtain ground connectivity. The challenge is to obtain a high-capacity connection between the train and ground able to support a train plenty 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. Furthermore, the traffic of many trains can be also aggregated in these points, known as break-out Internet points.

Typically, different business models lead to different strategies on where to locate these break-out points. A small railway service company that desires to offer this service can concentrate all the traffic for all the train and all the users in a unique cloud break-out Internet point, but another possibility is to distribute different break-out points along the track. This model is more scalable and seems more suitable for a multi-stake holder environment.

For the previous reasons, UC3 B1 locates the break-out points at the MEC layer.

The AP selected for the project is a Wi-Fi 6 [9] that operates in the existing 2.4 GHz and 5 GHz frequency bands (Wi-Fi 6 is the naming provided by the Wi-Fi Alliance to the 802.11ax standard). This AP supports peak rates of 1800 Mbps (600 Mbps in 2.4 GHz and 1200 Mbps in 5GHz) with extra low latency (less than 2 ms). This service will be demonstrated only in one vehicle.

3.2.3.1 Behavioural View

Figure 6 represents the behavioural view of the B1 service. As with the previous services, each step is represented by an encircled sequential number.

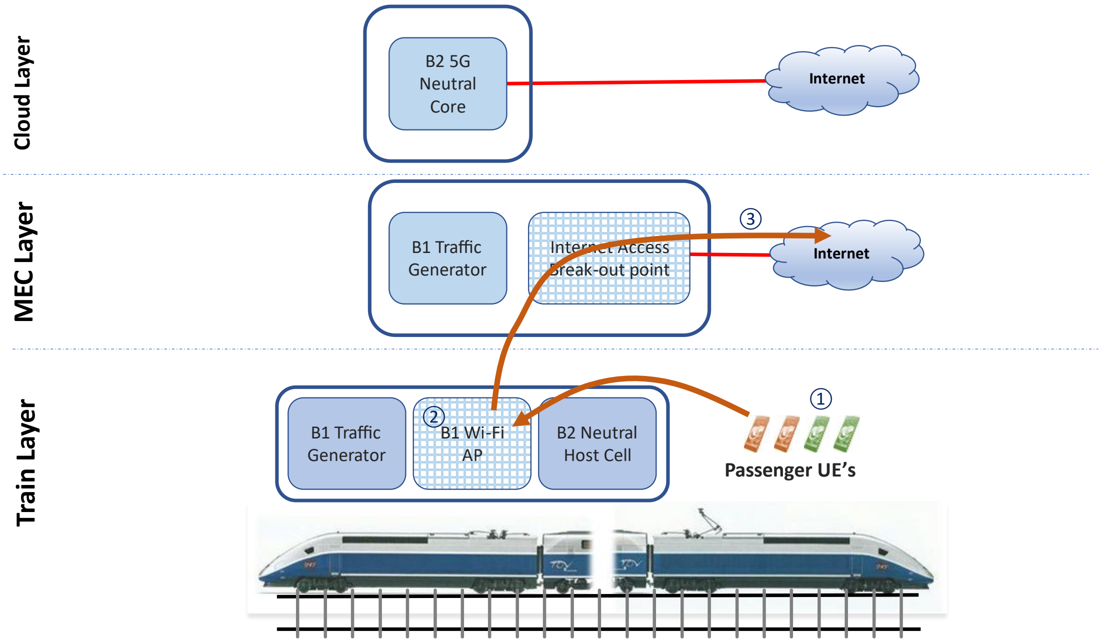

Figure 6 – Behavioural view for B1 High Quality Wi-Fi to passengers.

Passengers will connect their UEs ① to the Wi-Fi APs of their vehicles ②. The traffic of all the train passengers will be aggregated by the 5GMED Network in a router to reach a high-capacity break-out point to the Internet located in the MEC layer ③.

Regarding the Gigabit train concept [4], B1 will use traffic generators in order to simulate a train full of passengers accessing to the Internet as showed in Figure 7.

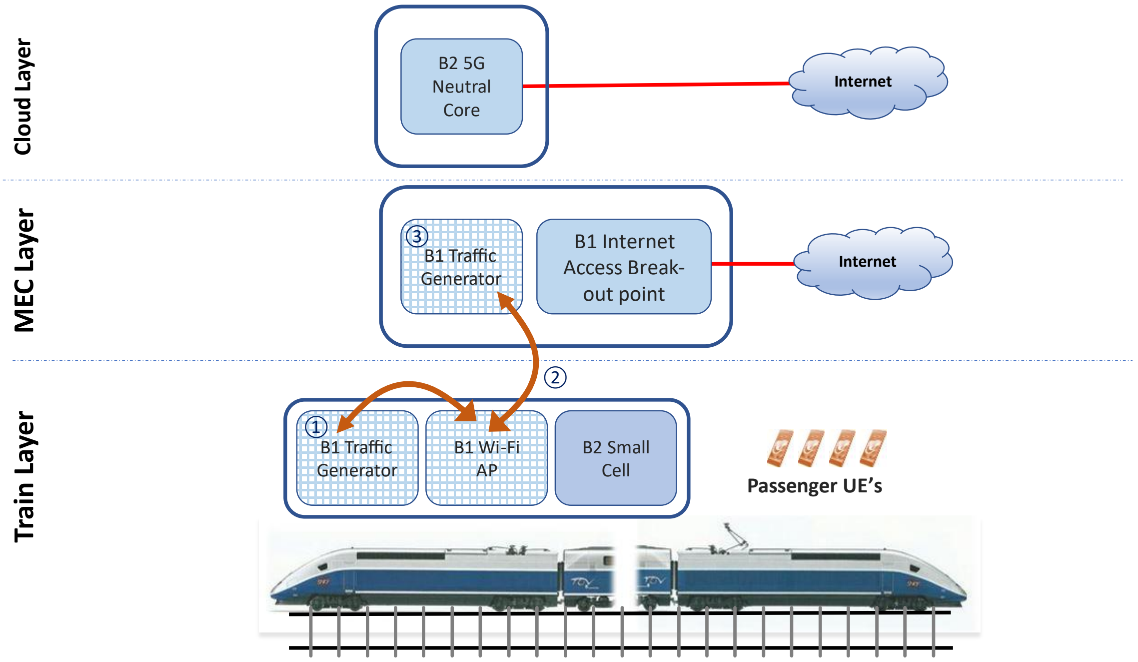

Figure 7 – Behavioural view for the B1 Gigabit train simulation.

3.2.3.2 Cross-border behaviour

Two different B1 Traffic generators (one in France and other in Spain) will be used in order to send/receive the traffic according to the train location (information obtained from the Geolocation Module defined in section 4.1.2) A script will be developed to automatize the traffic generation between the adequate endpoints. The change of these endpoints will be perceived by the B1 Traffic generators, that can tolerate the additional latency and interruption time in the range defined by the B1 service KPI's, that will be added to the similar effect induced by the use of roaming at the border.

In the case of the Internet Access of specific passengers UE connected through the B1 Wi-Fi AP, they will not experience any disruption of the service, because only a common break-out point for both countries will be deployed. It was decided to provision a common break-out point for both countries because the effect of moving from one break-out point to the other will restart the TCP session and, in case of UDP traffic, packets will be dropped until the next break-out Internet point will be reachable; in other words, exactly the same behaviour that the B1 Traffic generators will experiment with the change of the end-points.

3.2.3.3 Requirements

Table 4 shows the list of the B1 service components requirements. Cross-border requirements are marked with an asterisk.

ID	Functional Blocks affected	Requirement description	Importance
R-B1-001	B1 Wi-Fi AP	The Wi-Fi AP must provide a specific WLAN to connect the passenger's UE	Must
R-B1-002	B1 Wi-Fi AP	All passengers' UEs in the train must access to the Internet in aggregated way	Must

R-B1- 003	B1 Wi-Fi AP	B1 service must be compatible with different UEs (phone, laptop, and tablets) and common operating systems.	Must
R-B1-004	B1 Traffic Generator	B1 Traffic Generators must generate enough traffic to verify the Gigabit Train concept.	Must
R-B1-005 *	B1 Traffic Generator	At cross-border event, the train B1 Traffic Generator must be able to redirect the data flow to the ground. B1 Traffic Generator corresponding to the country the train is located.	Must

Table 4 – B1 service components requirements.

3.2.4 B2 Multi-tenant Mobile Service for Passengers

D2.1 [1] described this service as a new alternative to provide mobile connectivity inside trains with the use of on-board 5G small cells, which will connect the train to an on-ground 5G core. What we propose here is a gNB deployed in each train (named "neutral cell") together with the 5G core network deployed on ground (named "neutral 5G core"). This may constitute a neutral host MNO infrastructure that could be leased to national MNOs (e.g., French national MNO for French train operators and Spanish national MNOs for Spanish train operators in this specific example; but in a more general case other MNOs can be also involved: suppose the train belongs to an Italian railway company that desire to provide this service also to an Italian MNO).

The backhaul of the neutral cells in the train to the neutral 5G core on ground will use the 5GMED train to ground connectivity as defined in Section 4.

An example of the generic use of the neutral 5G core with the interaction of all these MNOs described above is illustrated in Figure 8.

Note that this Internet Access service is not the same that B1 provides because is controlled by the MNOs, not by the Infrastructure Manager and the train company. In Figure 8, MNO1 and MNO3 are using the 5G Neutral Core as break-out point while MNO2 are using their own break-out point.

Anyway, this example is too ambitious and the scope of B2 inside 5GMED must be simpler than this general case: the B2 deployment will only deploy the neutral 5G core in the ground, the neutral cell in the train and the UEs will use them only to provide Internet Access.

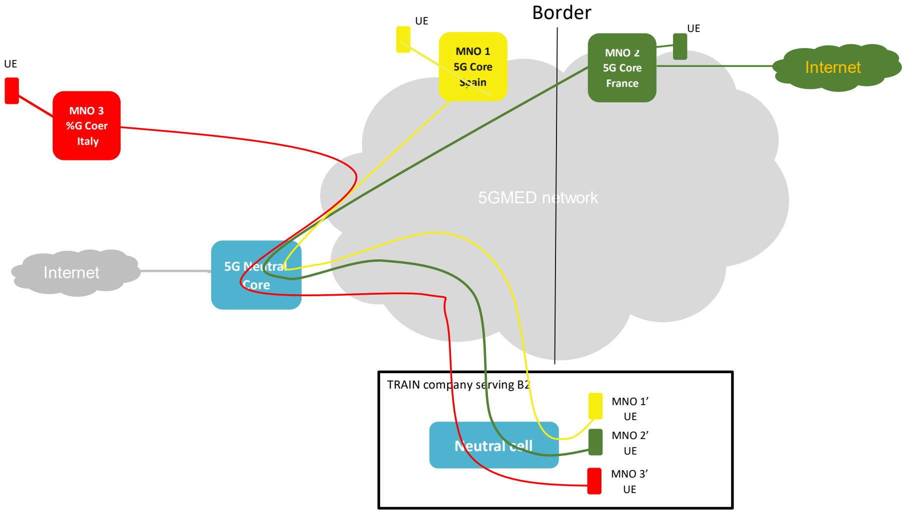

Figure 8 – Generic use of B2 service (using home routed roaming with national MNOs).

Therefore, the neutral 5G core for B2 will be different from the 5G cores used for the 5GMED Spanish or French MNOs. This Free 5GC will be located in the Cloud Layer of the 5GMED network architecture.

As in-train gNB, an Amarisoft Callbox classic will be installed inside the train to create the small cell in the train. In a commercial train this cell could be distributed throughout the whole train, along the different coaches using a DAS (Distributed Antenna System).

Regarding the radio carrier of the small cell in the train, test frequencies were requested to the French and Spanish frequency regulators. The purpose is to experiment the situation where the allowed frequencies are in different countries, i.e., on each side of the border are different. Then we have to implement a mechanism for the in-train gNB to change frequency when the train crosses the border using location provided by the GPS.

Finally, the lease of the neutral infrastructure could take the form of specific 5G slices for each national MNO. This extends the concept of multi-tenant Mobile service developed in the 5GMED proposal. In the case of satellite, we will explore and adapt a technology to keep the 5G slice end to end. This technology can be adapted to other access network technologies, but out of the scope of 5GMED.

This 5G neutral core will be a Free 5G core with a Session Management Function (SMF) that was modified by one of the 5GMED partners to allow maintaining 5G slices through the non 3GPP satellite access used for backhauling.

3.2.4.1 Behavioural View

Figure 9 represents the behavioural view of B2 service, Multi-tenant Mobile Service for Passengers. To simplify B2 service, it will be tested with the Internet Access of the UE passengers connected to the B2 small cell in the train -other MNO services can be provided in a similar way-. The B2 Internet Access is provided through the B2 5G Neutral Core and is different from the B1 Internet Access. Each successive step is represented by a sequential number encircled.

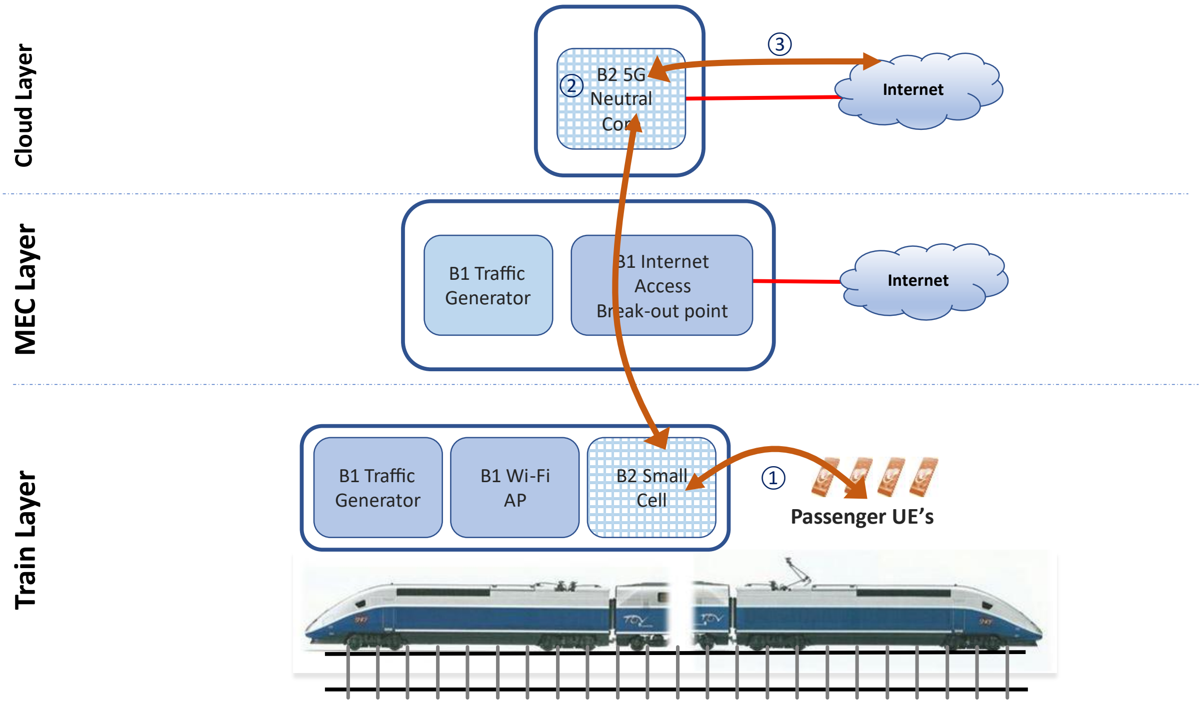

Figure 9 - Behavioural view for B2 Multi-tenant Mobile Service for Passengers.

Service is really simple. Passengers will connect their 5G UEs to the small cell of the train ①. The data stream will continue its way to reach the B2 5G Neutral core of the neutral host infrastructure② and then go to its final destination, in this particular case, the Internet Access for this service through the 2 Internet Access Break-out point. ③

This service will be demonstrated only in one vehicle.

3.2.4.2 Cross-border behaviour

As the UE is connected to the core network of the neutral host infrastructure, which is the same in both countries, there is no additional roaming for the UE at the core level. Crossing the borders will be quasi-transparent for the UE, except for the carrier change as different Absolute Radio Frequency Channel Number (ARFCN) might be used in the different countries.[3]

B2 can tolerate the additional latency and interruption time that will be induced by the use of roaming at the border in the range defined by these B2 service KPI's.

3.2.4.3 Requirements

Table 5 shows the list of the B2 service components requirements. Cross-border requirements are marked with an asterisk.

ID	Functional Blocks affected	Requirement description	Importance
R-B2-001	B2 small cell and 5G core	The Passengers' UEs must be allowed to connect to the small cell.	Must
R-B2-002	B2 Core	Support of Home Routed Roaming.	Could
R-B2-003 *	B2 small cell in train	A license for the radio carrier's frequency used by the small cell in the train for each country must be available.	Must
R-B2-004 *	B2 small cell in train & B2 Core	When crossing the borders, the radio carrier used by the small cell should change.	Must
R-B2-005	B2 small cell in train	The access to the B2 small cell will be exclusively limited to a set of UEs (phone, laptop, and tablet) with the appropriates SIM.	Must
R-B2-006	UE	Train MNO SIM card available for test UE's.	Must

Table 5 – B2 service components requirements.

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[3] In order to evaluate the impact of carrier change, we have tested a scenario where a UE is connected to an Amarisoft cell (located in the I2CAT lab) using band N77 and connected to the Free 5GC core (located in the IRT lab). Then, we connected another cell using band N78 to the same core and realized a handover for the UE. The measured interruption time was very small, and the delay was around 65 ms, basically due to the non-optimized backhaul used during this test. Furthermore, no packet loss was noticed when executing the carrier change.

4 Communication Blocks

This section describes the communication blocks that provide connectivity between the functional blocks on-board the train and the ones on ground. The network infrastructure layer (shown in Figure 1) is described in detail in deliverable D3.2 [7]. To explain the connectivity between the train and the ground devices, it is commonly accepted to use the following terminology [14]:

1. The **Train Communication Network (TCN)** interconnects all the service components and the on-board communication components inside the train.
2. The **Train Access Network (TAN)** provides connectivity between the train service components and the ground service components.

Figure 10 illustrates the TCN, the TAN, and the Network Infrastructure Layer of 5GMED independently of the location of the ground service components (Edge or Cloud Layers).

The remainder of this section is organized as follows. Section 4.1 describes the elements and requirements of the TCN. Section 4.2 describes the operation of the ACS-GW and the requirements of the TAN. Section 4.3 describes in detail the functional operation of the TAN. Finally, Section 4.4 details the cross-border issues related with the communication components.

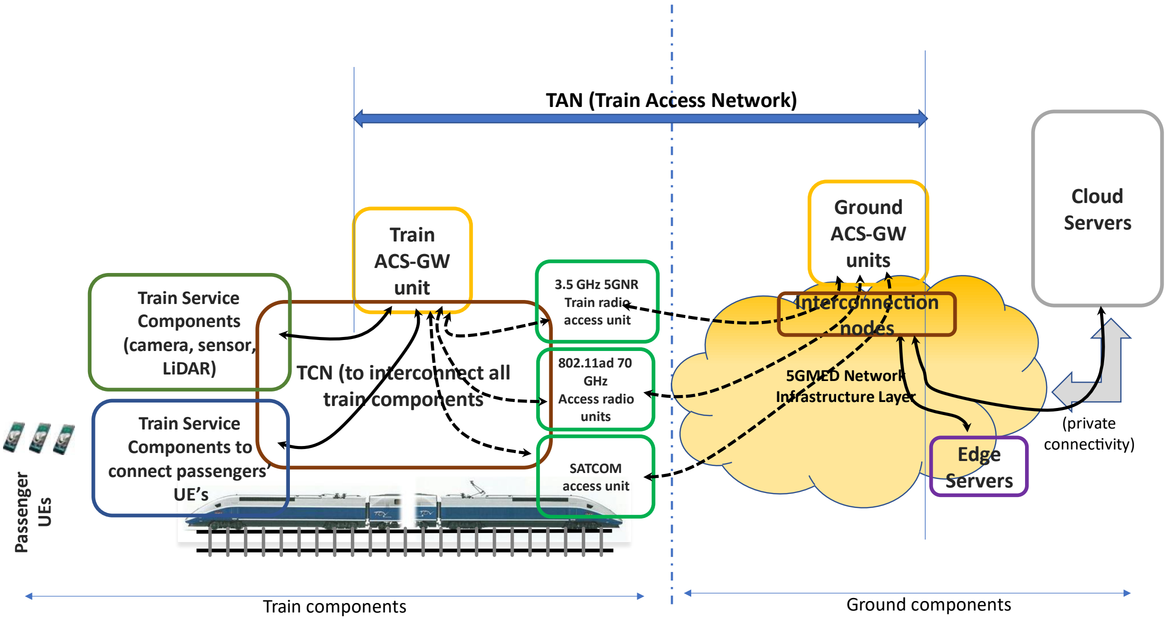

Figure 10 – TAN, TCN, and 5GMED Network Infrastructure Layer.

Funded by the Horizon 2020 Framework Programme of the European Union

4.1 Train Communication Network (TCN)

In the context of this project, the TCN refers to the infrastructure needed to interconnect all the devices installed on the train to provide UC3 services. It enables communication among all the identified train components (see Figure 11):

- All the devices needed to run the use cases' services described in Section 3.
- The TAN components that need to be hosted in the train to provide connectivity with the ground:
  - On-board Radio Access Units: the set of devices that provide connectivity to each radio access network, i.e., 5G NR, IEEE 802.11ad 70 GHz [15], and satellite. These components are described in section 4.1.1.
  - Geolocation module: a specific module that provides the train location to the different train devices that need to obtain it. Section 4.1.2 describes this module.
  - The ACS-GW train unit. Section 4.2 is dedicated to describing the behaviour of the ACS-GW units.

Passenger UEs (e.g., mobile phone, 5G modem, or laptop), are not connected directly to the TCN. They will use the Wi-Fi Access Point of the B1 service or the B2 small cell of the B2 service to reach 5GMED ground service components and the Internet or the small cell of the B2 service to establish MNO videoconferences.

To avoid the interference between the 5GMED components and devices currently installed in the trains used for testing, a separated and totally isolated TCN should be built. This isolated TCN will provide connectivity between all the components and devices needed for a successful project implementation.

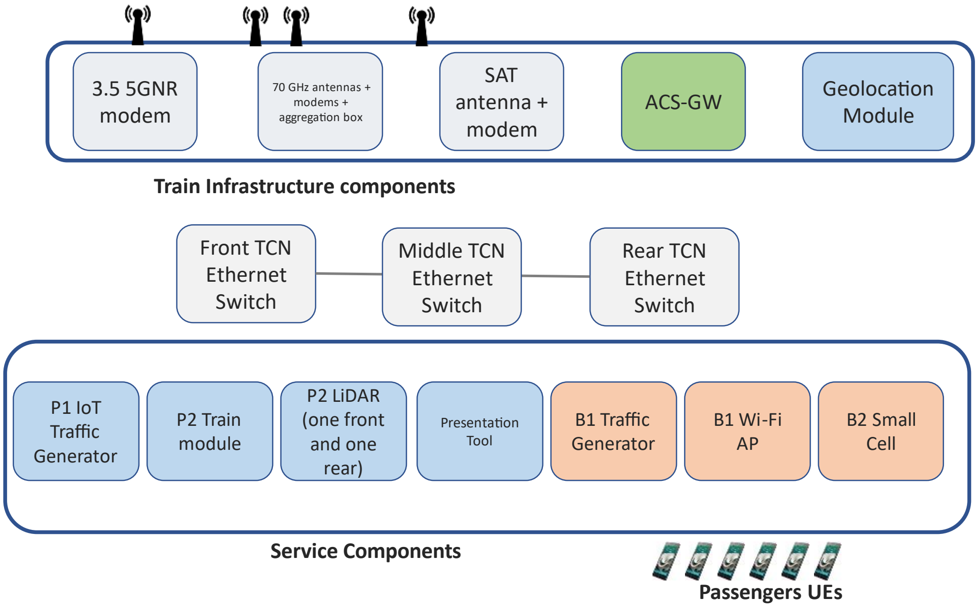

Figure 11 – Expected TCN components for 5GMED.

To achieve the maximum train-to-ground network performance, the TCN switches must provide different types of Ethernet interfaces (10Gbps optical, 1 Gbps optical. 1 Gbps copper, 100 Mbps copper) to connect the different on-board devices, and their trunks must support up to 10 Gbps; otherwise, the TCN itself could be a bottleneck. For fulfilling those requirements, a single-mode optical fibre should be deployed along the train.

It would not be reasonable to deploy this network in the whole train. To minimizes the impact of the introduction of new devices on the train, only the most relevant train vehicles will be used. For this reason, the following will be required:

- An intermediate vehicle with enough room to support a major part of the service components.
- Two vehicles at each end of the train (or near each end), to locate the multiple antennas and some specific service components (e.g., a LiDAR for the track obstacle detection service).

4.1.1 On-train Radio Access Units

This section describes all the radio access units that must be installed on-board the train to provide connectivity to the different radio access networks of 5GMED: 3.5 GHz 5GNR, IEEE 802.11ad [15], and satellite.

4.1.1.1 3.5 GHz 5GNR 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 the 3.5 GHz antenna and the 5G modem:

- The antenna model to be installed on the train roof will be a Huber+Suhner model 1399.17.0222 [16]. The chosen antenna is a 2x2 MIMO railway rooftop antenna that supports frequency bands from 617 to 960 MHz and 1350 to 7125 MHz. Therefore, this model supports the 3.5 GHz band that will be used in the 5GMED 5G network.
- A Quectel RM500Q-GL 5G modem [17] will be installed inside the train. This modem supports several radio bands including N77 and N78 that will be used in the project. It also supports 5G SA and 5G NSA networks. Both 2x2 and 4x4 MIMO configurations are enabled by the modem, which allows it to provide data rates up to 2.5 Gbps in downlink and 900 Mbps in uplink (in ideal environment).

From one side the modem will be connected to the TCN through a computer, and from the other side to the 5G antenna. The latter will communicate with the ground via the 5GNR gNodeBs installed along the corridor as explained in Deliverable D3.3 [8]. Figure 12 shows the connectivity diagram of the 3.5 GHz radio access.

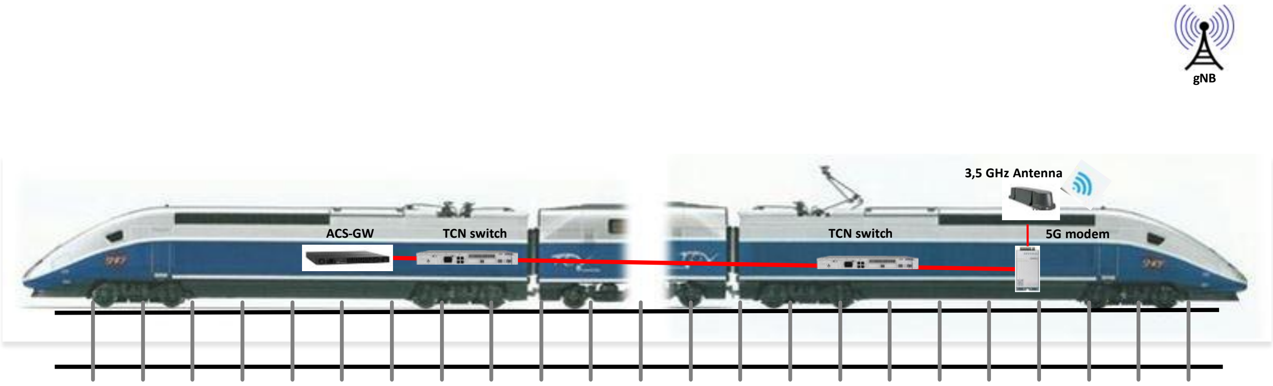

Figure 12 – On-board 3.5 GHz 5GNR radio access architecture.

4.1.1.2 IEEE 802.11ad 70 GHz Radio Access Unit

The network based on this technology, described in D3.2[7], will provide high performance train to ground connectivity. Units inside the train are connected to the trackside units via electronic self-directed beams between them and using IEEE 802.11ad.

Each train will contain two radio units, located at the train head and the train tail. In a similar way, reverse and facing antennas are located on every trackside pole (See Figure 13).

Figure 13 – IEEE 802.11 ad 70 GHz self-directed beams.

Each unit on the train roof contains also two antennas pointing in opposite directions: the front unit shall be connected to the nearest pole in the direction in which the train is moving. Once the connection is made, the ground antenna will follow train's movement, using advanced beamforming techniques. The beam shall continue to be aimed at the rear unit of the train as the train moves forward. The process continues through the successive ground antennae along the track.

The on-board antennas and the antennas on the ground need to be directly visible to each other (direct line of sight). Obstacles in between, such as vegetation, will prevent a good connection. Possible obstacles on the roof of the train itself (e.g., pantographs) must be considered.

In the train, the following components must be deployed:

- The two radio units described above as Figure 14 shows. Each unit is mounted at the end of the train. It consists of:
    - a roof element (with two antennas each one, faced in opposite directions),

  - a Network Processing Unit (NPU), a separate unit that is mounted inside the train in the roof attic near the radio pod to process the radio associations with the trackside units.
  - These two components are connected via a Peripheral Component Interconnect Express (PCIe link, a standard high-speed serial computer expansion bus). Due to this, the maximum distance between the NPU and the roof antennas must be lower than 2 m.
- An aggregation appliance box inside the train. This component establishes multiple data-streams across available links to provide increased throughput and ensure link redundancy and resilience.

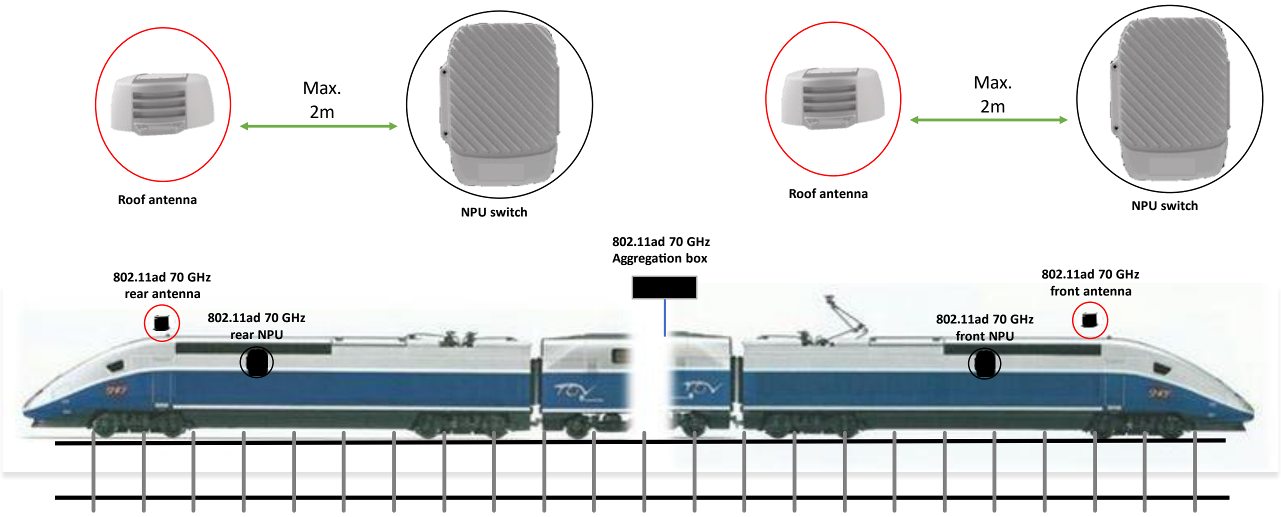

Figure 14 – IEEE 802.11ad 70 GHz on-board components.

Figure 15 shows the connection between the 802.11ad 70 GHz components the rest of the common train infrastructure components. Note that all the connections in Figure 15 are based on 10Gbps Ethernet ports (except the PCIe link between the NPUs and the antennas on the roof).

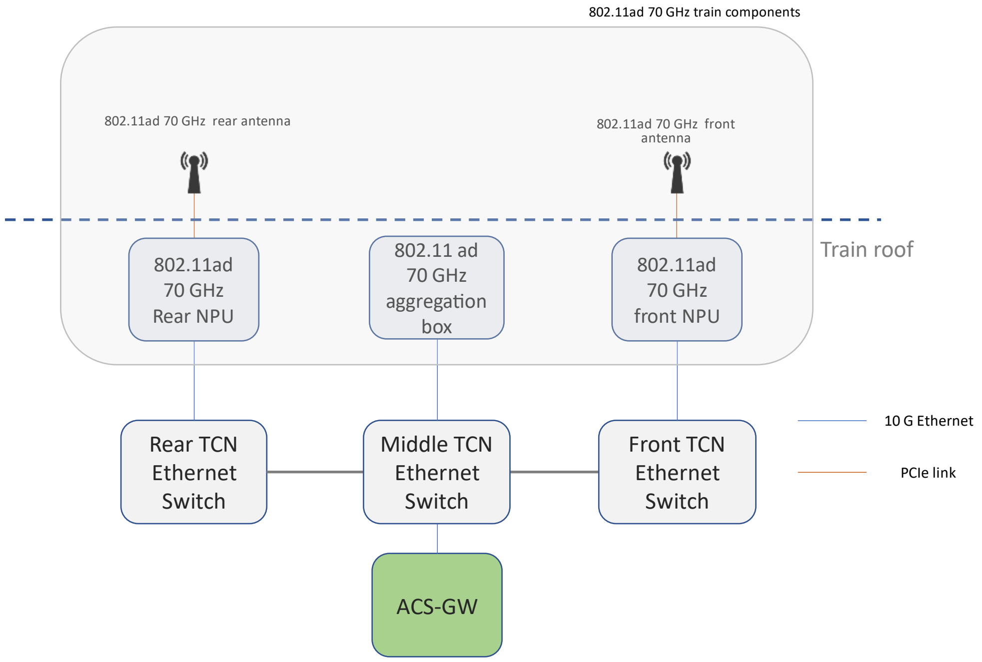

Figure 15 – On-board 802.11ad 70GHz radio access architecture.

The ACS-GW will use the 802.1ad 70 GHz aggregation box as the entry/delivery point to receive/send packets from/to this network.

4.1.1.3 Satellite Radio Access Unit

For the direct satellite connectivity between the ground and the train, the main devices required for the on-board infrastructure are the satellite antenna and the satellite modem.

a. **Mobility satellite antenna:** A satellite communication antenna with low profile located on the roof of the train, designed to receive or transmit information by radio waves to or from a communication satellite. FPAs (Flat Panel Antennas) with low profiles and high bandwidth efficiencies are changing satellite industry, improving technological and business aspects, and opening new services for satellite industry.

   The selected antenna has been based on a Gilat Raysat ER7000 [18]. it is a reliable, low profile antenna system that enables real-time K_a band[4] broadband satellite communications for video, voice, and data transfer, suited for trains and large vehicles. The ER7000 is designed to handle the challenging environmental conditions and extreme changes common in mobility applications.

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[4] Portion of the electromagnetic spectrum in the range 26.5–40GHz frequencies

b. **Satellite modem**: A SATCOM modem will be in a rack inside the train, connected to the TCN. This HT2500 satellite modem [19] is employed to set up data transfers using a communications satellite to rebroadcast the information. Via the TCN, the modem is connected to the ACS-GW.

The satellite antenna on board will connect to satellite (via HISPASAT satellite network), then the satellite connects to the ground station, usually named teleport, located at Arganda del Rey (Madrid, Spain). Then packets transmitted will be sent to the 5GMED network via ethernet. This connectivity is described deliverable D3.2 [7].

Figure 16 shows the connectivity diagram of the satellite access inside the train.

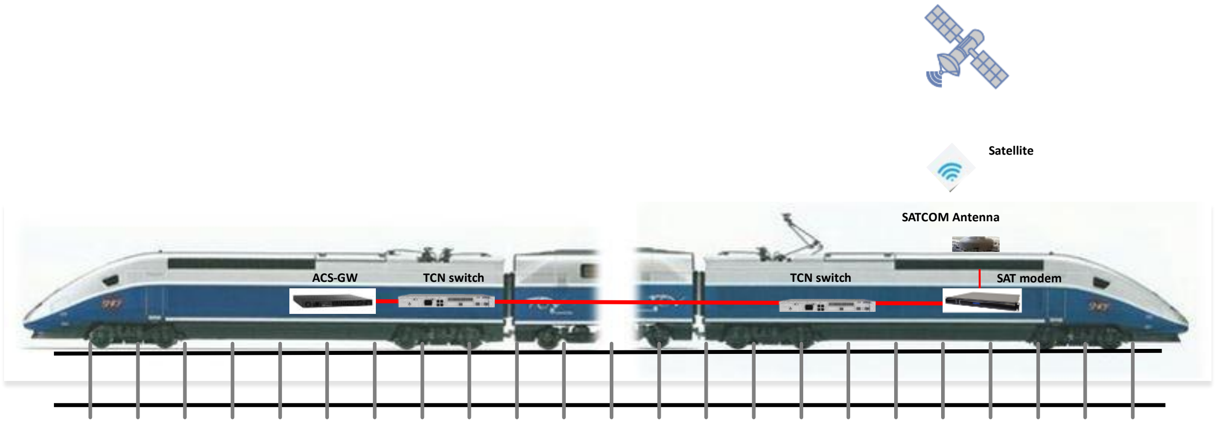

Figure 16 – On-board SAT radio access architecture.

4.1.2 Geolocation modules

A specific software geolocation module will be developed to distribute the train position to the rest of the railway components with enough accuracy for the project purposes. It is planned to develop two different software modules: one version for the train and another version for the ground.

Initially, inside the train, at least the ACS-GW train unit, P2 train module, the B1 Traffic generator, and the B2 small cell need to know the train position.

On the ground, train position has to be provided to some components on the MEC layer: the ACS-GW ground units, the P2 AI modules and B1 traffic generators.

As for the actual component deployment, the most suitable approach is to implement the train and ground geolocation modules within the B1 service PC-NUCs: in this way the geolocation modules are also co-located with the ACS-GW units in train and ground.

The train geolocation module obtains the location from the IEEE 802.11ad 70 GHz units installed on both train heads. Each NPU integrates a GNSS receiver module. The refresh rate of the GNSS receiver is 2 Hz, which means that in the TGV at the maximum speed of 300 km/h, two consecutive position measures will have up to 41,65 m difference. This was considered valid for the 5GMED service components that need the information of the train position.

Once the train geolocation module receives the information provided by the GNSS receiver it will use this information, the length of the train, and a map with the theoretical coverage of the different radio access networks along the corridor to calculate the following data.

- Absolute geographical coordinates (Latitude and longitude). A specific procedure must be identified to inform when the train is inside the Le Perthus tunnel, because it is expected that the GNSS module does not provide information in this case.[5]
- Train Speed.
- Country (France or Spain).

In the train, the geolocation module will periodically transmit this information to a multicast group [20] using the TCN, and every client inside the train that needs this information must subscribe to this group.

The geolocation module in the train will retransmit this information to all the ground geolocation modules (all the edges locations are interconnected by the 5GMED backhaul), adding to the geolocation info a train timestamp in these messages. This timestamp will be used to prevent a hypothetic disorder of the packets received by a ground module, considering valid only the ones with a bigger timestamp than the previous.

The on-ground components that need to obtain the train position will receive the required information from these ground geolocation modules.

4.1.3 TCN Requirements

Table 6 shows the list of the TCN components requirements.

ID	Functional Blocks affected	Requirement description	Importance
R-TCN-001	TCN switches	TCN switches must provide Ethernet interfaces (ports) in the range of 10 Gbps optical – 1 Gbps optical – 1 Gbps copper – 100 Mbps copper to connect the different on-board devices.	Must
R-TCN-002	TCN switches	TCN trunks must support up to 10 Gbps; otherwise, the TCN itself could be a bottleneck. For fulfilling those requirements, a single-mode optical fibre should be deployed along the train.	Must

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[5] The existence of the Le Perthus tunnel was introduced to the reader in D2.1 [1] section 2.1. The existence of this tunnel will be relevant also for the section 4.4 topics.

R-TCN-003	TCN switches	Switching capacity greater than 1 Gbps.	Must
R-TCN-004	TCN switches	TCN switches must be able to insert/drop a default VLAN tag per port.	Must
R-TCN-005	TCN switches	TCN switches must be able to pass transparently incoming packets with a VLAN tag different for the default one.	Must
R-TCN-006	TCN switches	TCN switches must be able to forward service flows to a specific set of ports of the ring.	Should
R-TCN-007	TCN switches	train service components and passengers train service components must be in different VLANs.	Must
R-TCN-008	TCN switches	Each train RAT must be in a different VLANs.	Must
R-TCN-009	Train Geolocation module	The module must be able to provide the train position to the train modules that request it.	Must
R-TCN-010	Train Geolocation module	The module must be able to provide the train position to the ground geolocation modules.	Must
R-TCN-011	Ground geolocation modules	These modules must be able to request the train position to the train geolocation module.	Must
R-TCN-012	Ground geolocation modules	These modules must be able to provide the train position to the ground components that request it.	Must
R-TCN-013	Train and ground geolocation modules	All the issues related with train position will be consider an error or 42 m. when the TGV will be used.	Must
R-TCN-014	Any Radio Access Technology Component	Any RAT in the train must be EN50121 (Railway EMC compliant [21]).	Must

Table 6 – TCN components requirements.

4.2 Train Access Network (TAN)

The Train Access Network (TAN) is the network created between the service components in the train and the service components in the ground.

Before 5GMED, a generic TAN is composed of (see Figure 10 in the introduction to section 4):

1. The different radio access technologies that are deployed along the rail track segment. In 5GMED, these radio access technologies are: 5G SA network, 802.11ad 70 GHz network and satellite, which are integrated into the 5GMED Network along the cross-border corridor[6].
2. The different access units on the train of each of these access technologies.
3. The gateway units, components that integrate and manage the different access technologies. While a train gateway is needed in all cases, depending on the requirements, one or more ground gateway units will be needed.

One of the UC3 requirement described in D2.1 specifies that the gateways must be able to select the preferred access technology for each service individually. Additionally, seamless connectivity to all the services is required along the cross-border scenario: Mobility interruption time KPI was defined for each one, specifying how much time a service can remain without connectivity. That means the TAN must cope with the handovers. Handovers are commonly classified in two types: vertical and horizontal.

Vertical handovers will occur when the train moves across different types of radio access networks along the corridor. The reason behind this handover is that these radio access networks are not available everywhere in the railway track between Figueres and Perpignan. For this reason, 5GMED will develop specific gateways, called Adaptative Communication System Gateway (ACS-GW). This gateway is provided with mechanisms to identify and select the most appropriate radio access technology for each UC3 service. There are two types of these gateways: Units inside the train and units on ground.

Some additional features must be mentioned:

1. The radio access technology selected to deliver a specific UC3 service may differ. The selection method to choose which is the preferred radio access technology for each of these services will be configurable.
2. In absence of handovers, the radio access network selected for each service will be the same for both directions (i.e., train to ground and ground to train). In case of handovers, uplink and downlink will also use the same technologies.
3. The ACS-GW ground unit used depends on the train position. Each ACS-GW ground unit must be associated with a particular segment of the track (using latitude and longitude) in a way that the traffic originated and destined to the train in a given position will be managed by the corresponding ACS-GW ground unit associated to the train absolute coordinates. This is particularly useful in a cross-border situation.

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[6] A complete description of the 5GMED network architecture and the coverage of the different radio access technologies that composes the 5GMED Network is presented in deliverable D3.3[8].

4. TAN can be defined also as all the communication components between the ACS-GW train unit and the ACS-GW ground units on the ground, including themselves and the 5GMED Network layer. Once a packet arrives at the ACS-GW train unit, it is delivered transparently to the ACS-GW on-ground and vice-versa.
5. The ACS-GW units will be also responsible to implement the mechanisms used to identify and select the most appropriate access technology for each specific UC3 service.

In the 5GMED corridor, there are two ACS-GW ground units: One ground ACS-GW is located in Spain and another ground ACS-GW is located in France. It means that the Spanish ACS-GW is used when the train is in Spain, and when the train is in France, the French ACS-GW is used. In this way, traffic inside the TAN will be forwarded to the corresponding country according to the train This process will be independent of the ACS-GW features.

What is included in sections 4.2 and 4.3 is a complete description from the service point of view, explaining the expected end-to-end behaviour for each service, i.e., what is the normal behaviour of the TAN under normal operating conditions and the reaction of the TAN to handovers. It is not necessary to know the specific coverage map of the different radio access, as the ACS-GW units should automatically react to its variation (due to failures, maintenance position. The information related to the geolocation modules in the ground is included in section 4.1.2.

Furthermore, and due to the corridor characteristics, a horizontal handover will occur when the train moves from one country to the other, due to the roaming process established between the 5G MNOs at each side of the border.

As a result, to understand the TAN behaviour related to each service, the following points are described in the different subsections:

- A high-level description of the ACS-GW modules (section 4.2.1)
- ACS-GW General Principles (section 4.2.2): A functional description of the ACS-GW modules, including their main features.
- Vertical Handover between different Radio Access Technologies (RAT) in section 4.2.3: this process will be managed by the ACS-GW units.
- Railways Cross-Border Scenario (section 4.2.4): describes the TAN requirements in this specific cross-border area.

4.2.1 ACS-GW Description

The ACS-GW units will be implemented as kernel-based virtual machines (KVMs) [22] hosted on Linux servers and directly connected to 10 Gbps network interface cards through a PCIe passthrough.

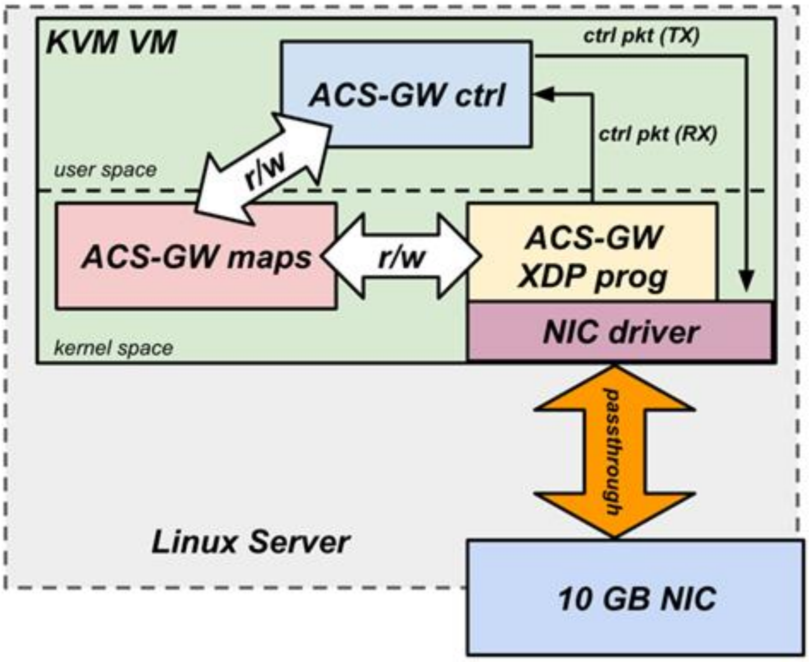

Figure 17 – High level architecture of the ACS-GW.

The ACS-GW consists of two main components, as described in Figure 17:

- The data plane forwards the packets and manages the session flow according to the policies that are installed by the control plane. This is implemented within the eXpress Data Path framework (XDP) [23] provided by the Linux kernel that makes it possible to perform high-speed packet processing within extended Berkely Packet Filter applications (eBPF) [23], that allows, among other things, analyse network traffic. The XDP program with this data plane matches in Figure 17 with the ACS-GW maps block and the ACS-GW XDP prog block, both in the kernel space.
- The control plane agent, configures the data plane, checks the status of the access network units (3.5 5GNR, 802.11 ad 70 GHz and satellite), and shows some info to the user, for example, the table used for service flows classification. The program with this control plane is represented in Figure 17 with the blue ACS-GW ctrl block in the user space.

4.2.2 ACS-GW General Principles

To illustrate the behaviour of the ACS-GW units, it is necessary to define a service flow. A service flow is a set of IP packets exchanged between one or more train service components and ground service components. It is identified by defined values in some selected packet header fields, as will be explained in the Packet classification section. The ACS-GW unit inspects the header of all the incoming packets, to classify them as belonging to one of the services flows predefined in the configuration file.

The ACS-GW units implement an intelligent dynamic forwarding strategy, applying a customized forwarding policy for each predefined service flow. If the packet cannot be identified to any of them, a default forwarding policy can be applied (for example, drop the packet).

4.2.2.1.1 Packet classification

The actual traffic classification mechanism is a multi-field wildcard matching based on the following packet header fields:

1. VLAN tags: this field provides the first level of classification, and it will identify the type of end user devices (cameras, end devices connected to the Wi-Fi Aps, sensors, etc...).
2. Transport Layer Ports: these fields go into the details of the specific service protocol and should be sufficient to understand the nature of the service traffic flows (and thus to derive the relevant target parameters).
3. IP addresses: these fields could be used to differentiate different traffic encapsulated in the same service protocol (e.g., WEB browsing VS streaming over HTTP) or to simply bind QoS parameters to source IP addresses.
4. GTP tunnel parameters: these fields are used to match services sent through the train B2 small cell.

The TCN switch is responsible for the VLAN tagging of the ethernet frames coming from the end devices (e.g., cameras, sensors, or PCs connected to the train). The ACS-GW leverages this function by simply inspecting the VLAN tag will route the flow to the corresponding radio technology.

If this VLAN tagging mechanism is not sufficient (i.e., the same device generates traffic from different services and with different forwarding requirements), the ACS-GW can leverage two further classification strategies:

- It may inspect the transport layer ports of the incoming IP packets. For example, in this way it is trivial to differentiate service protocols (e.g., HTTPS, SSH, VPN tunnelling, etc.).
- If the identification of the service protocol is not sufficient to understand the matching QoS target requirements (e.g., video streaming and web browsing over HTTPS), the ACS-GW may inspect the destination IP address of the incoming IP packets. In this case, it would be easy to understand if a HTTP flow is used to communicate with a video streaming server in the MEC or with other content providers on the Internet.

Other mechanisms could be implemented, but for the sake of the project, only these ones will be implemented. It must be highlighted that the packet classification is restricted to the packet headers. The payload of the packets is not inspected at all.

4.2.2.1.2 Forwarding policies

Since the ACS-GW processing must be transparent to the end user services and devices, the project is not considering a dynamic resource reservation mechanism. Undoubtedly, we can already state that a dynamic plug-and-play solution able to work in any scenario will not be provided. Instead, we can think of a simpler approach in which, for each service flow, we associate a priority list that defines the preferred networks to use.

Just as an example, we can think of two simple forwarding policies:

- Policy 1: High Throughput
- Policy 2: Best Effort

In this case, Policy 1 could be associated with a priority list including only the two high throughput rates radio access networks (i.e., 5GNR and IEEE 802.11ad 70GHz), and Policy 2 could include all possible radio access networks (i.e., 5GNR, IEEE 802.11ad 70GHz, and satellite).

Similarly, the radio access network priority list could also consider the train's position. For example, Policy 1 could consider the following priority lists:

- From km A to km B: 5G NR, IEEE 802.11ad 70 GHz, satellite
- From km B to km C: IEEE 802.11ad 70 GHz, satellite.
- From km C to km D: 5G NR, satellite

This can be combined with some kind of RAN coverage and signal quality map to realize a more flexible and adaptive multi-connectivity forwarding strategy.

4.2.2.1.3 Connectivity check procedure

Once the forwarding policy is associated to the incoming packet, it is necessary to check if the selected RAT is available at this moment.

In this section, we describe the procedure that the ACS-GW units use to declare a connection available. We also explain the method defined when only one train unit and one ground unit are involved. To understand how this procedure works with multiple ground units, you must refer to section 4.4.3 after reading this section.

From a general perspective, the ACS-GW train unit will try to establish UDP/IP tunnel with the ACS-GW ground unit (see Figure 18). In the 5GMED testbed there are three networks: the 5G SA network at 3.5 GHz, the 802.11ad 70 GHz network, and the satellite network. For each of these technologies there is a different tunnel defined by the ACS-GWs units. At start-up, the ACS-GW train unit tries to establish the UDP/IP tunnels associated with each of the three networks. This initial process is needed to check which networks are available. The endpoint of the tunnels is based on the train position: must correspond to the IP addresses defined in the ACS-GW ground unit corresponding to the country the train is located. Basically, it will send a keep-alive packet encoded with the same tunnel specification of the UDP/IP tunnel to be established each 0.5 seconds (this timer is configurable). If a connection is available with this network technology, the keep-alive packet will eventually reach the ACS-GW ground unit, which will respond with an acknowledgment packet. The response is perceived by the train unit as the successful creation of the tunnel, through which service traffic can be directed. Similarly, the ground unit declares a radio access network available as soon as the corresponding tunnel receives the keep-alive messages from the train unit.

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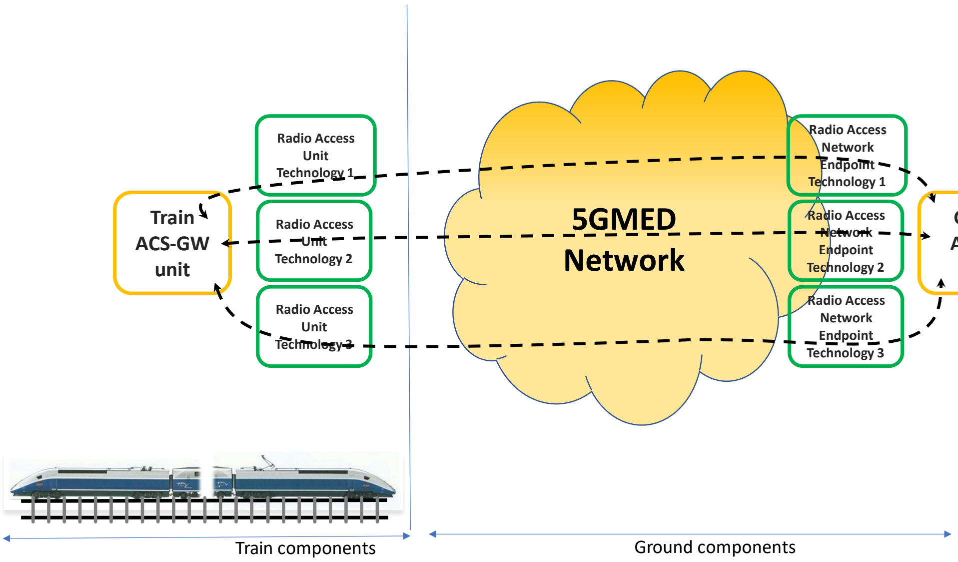

Figure 18 – IP/UDP tunnels between ACS-GW units

To know when a RAT becomes unavailable, both ACS-GW units maintain a timer with a configurable timeout. This timeout is reset after the successful reception of an acknowledgment message (for the train unit) or a keep-alive massage (for the ground unit). If a keep-alive or acknowledgment message is not received within the configured timeout, the RAT is marked as unavailable. Initially, the value of this timer is 2 seconds, and it is configurable.

This process will be periodically repeated to monitor the availability of all tunnels by sending these keep alive messages with a configurable period and checking for the respective acknowledgments.

In this way, any ACS-GW unit (either train or ground) can define an availability status associated with each radio access technology.

4.2.2.1.4 Packet encapsulation process

Any ACS-GW unit knows the forwarding policy to apply to a particular packet and the availability status of each of the radio access technologies. In this way, it is able to forward the packet to the preferred active connection.

Then, the IP packet will be encapsulated in another IP packet (IP over IP/UDP tunnel). An outer header is added, with the source/destination IP addresses corresponding to the specific tunnel for this radio access technology.

It is important to highlight a very specific requirement for all service components: in order to avoid IP fragmentation due to this encapsulation process; the service components are required to adjust the MTU value in order to account for the additional overhead introduced by the IP/UDP encapsulation (20 bytes IP + 8 bytes UDP). In order to facilitate this, the MTU value will be adjusted via DHCP, in an automatic way.

The reason to avoid packet fragmentation is that affects the performance of the data plane XDP program described in section 4.2.1.

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4.2.3 ACS-GW Packet Forwarding

4.2.3.1.1 Generic process

Once these general principles are described, it is possible to describe how the ACS-GW processes the packets.

It is said that the service flow is initiated by the train if the first packet of this service flow is generated by a train service component. The other way round, it is said that the service flow is initiated by the ground if the first packet of the service flow is generated by a ground service component.

Roughly speaking when any ACS-GW unit receives an incoming packet from a service component, it :

a) classifies this packet as belonging to one of the predefined services flows in the configuration file,

b) obtains the associated forwarding policy based on this classification,

c) checks the availability status of the radio access technologies to select the tunnel,

d) encapsulates the packet and forward it.

If the packets come from a radio access technology unit, simply de-encapsulates the packet and forwards it to the final destination.

When a unit receives a packet, it records the tunnel the packet came from and uses it to forward the packet of the same service flow. That implies that the service flow will use the same tunnel for both directions. This feature, named reverse path forwarding, increases the entire system's reliability and the performance, optimizing packet loss rate. This mechanism may improve some service KPIs as the UL/DL reliability and the service interruption time.

4.2.3.1.2 VLAN-ID handling

If the TCN uses VLANs, the ACS-GW train unit must be connected to the TCN in trunk mode to receive all Ethernet frames regardless of their VLAN-ID. The same applies to ACS-GW ground units.

The use of VLANs requires an additional feature for the ACS-GW units. Whenever sending a packet to a layer 2 switch, the VLAN-ID field of the corresponding Ethernet frame header must be filled in appropriately. In other words, the ACS-GW unit must know the VLAN structure of the TCN using a configuration file.

4.2.4 TAN Requirements

Table 7 shows the list of the TAN components requirements. Cross-border requirements are marked with an asterisk.

ID	Functional Blocks affected	Requirement description	Importance
R-TAN-001	ACS-GW train & ground units	TAN must transparently intercept the packets sent to/from the train service components from/to the ground service components.	Must
R-TAN-002	ACS-GW train & ground units	The ACS-GW units must passively classify service flows by inspecting	Must

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		VLAN tags, IP addresses and transport layer ports according to rules defined in section 4.2.2.	
R-TAN-003	ACS-GW train & ground units	The ACS-GW units must associate a set of forwarding policies to the active service flows according to the rules defined in section 4.2.2.	Must
R-TAN-004	ACS-GW train & ground units	The ACS-GW units must keep track of the active service flows.	Must
R-TAN-005 *	ACS-GW train & ground units	The ACS-GW train unit must deliver the traffic to the correspondent ACS-GW ground unit according to the train position.	Must
R-TAN-006	ACS-GW train & ground units	The ACS-GW ground units must forward the traffic to the ACS-GW train unit according to the TAN segmentation (section 4.4.3).	Must
R-TAN-007	ACS-GW train & ground units	The TAN must enforce automatic vertical handovers according to section 4.3.	Must
R-TAN-008	ACS-GW train & ground units	The ACS-GW units must forward packets at 10 Gbps. line rate.	Must
R-TAN-009	ACS-GW train & ground units	The ACS-GW units must be able to manage the origin/destination VLAN_IDs according to the rules defined in section 4.2.3 (VLAN-ID handling).	Must

Table 7 – TAN components requirements

4.2.5 TAN treatment of Vertical Handovers

The process described in the previous section illustrates how the ACS-GW units will manage the Vertical Handovers: packets will always be encapsulated over a tunnel corresponding to an active radio access technology. As was explained in section 4.2.2, a radio access technology is declared available if the corresponding tunnel is up (this condition is checked with the connectivity link procedure, as described in subsection 4.2.2.1.3).

As the forwarding policies are described in order of preference, the service flow will always use the preferred active connection defined in the configuration file. Thus, if the preferred link of service flow becomes unavailable (again, this condition is checked with the connectivity link procedure), the packets will be automatically forwarded to the next one specified in the policy associated to the service. Since the tunnels employ UDP/IP encapsulation, the original IP header is preserved. In this way, the handover is transparent for the application. Anyway, packet losses can occur during the handover, which will be handled by the transport layer. To mitigate the effect of this, the Vertical Handover triggers can be tuned to minimize packet loss as explained in Section 4.2.2.1.3. Note that this process only affects service flows that are forwarding traffic over the unavailable link. Service flows using other connections will remain unaffected. Similarly, once the preferred connection becomes available again, traffic will be restored to it.

Table 8 is a high-level representation of the forwarding policies derived from the UC3 requirements at the time of writing this document, oriented to test a complex variety of possibilities. Each row in the table maps the service ID to the RAN preference list. This list is configurable in the ACS-GW and can be modified to fit the requirements of a wide variety of situations. For example, in Table 8 service P1 has the following RAN priority list: Satellite, 3.5 GHz 5GNR, and finally 802.11ad 70 GHz.

Service Flow	**ACS-GW forwarding priority**		
	3.5GHz 5GNR	**IEEE 802.11ad 70 GHz**	**Satellite**
P1	2	3	1
P2	1	2	-
B1	2	1	-
B2	2	3	1

Table 8 – Example of ACS-GW Forwarding Policy.

In Table 8, each UC service has been identified with a different service flow, which is a straightforward example. If a service is composed by different patterns of traffic with different requirements, it is possible to divide in service flows if their patterns can be classified (examples: origin IP address, destination TCP port).

Another example is showed in Table 9. A railway company requests all the traffic to use 3.5 GHz 5GNR as the preferred radio access, backed-up by the rest of the access-technologies; but passengers' services must rely only on the IEEE 802.11ad 70 GHz network. The use of VLANs in the TCN will allow the use of simplified rules to build the ACS-GW table based on this. Then, if all the service components are connected to the TCN with the VLAN-ID 10 and the passengers' services components will use VLAN-ID 20, Table 9 will show properly the situation.

Service Flow	**ACS-GW forwarding priority**		
	3.5 GHz 5GNR	**IEEE 802.11ad 70 GHz**	**Satellite**
P1 P2 (VLAN 10)	1	3	2
B1 B2 (VLAN 20)	-	1	-

Table 9 - Example of a simplified ACS-GW forwarding table.

Finally, the ACS-GW units are able to execute automatic predefined vertical handovers based in the train position. Geolocation modules (section 4.1.2) update the ACS-GW units (train and ground) with the train geolocation info. The ACS-GW units (train and ground) are able to use several forwarding priority tables. Before select the radio access network to forward a packet, it will check with forwarding priority test must be used corresponding the current train position.

As an example, 5GMED project will test a 3.5 GHz 5G NR gNodeB in the Spanish side that includes satellite backhauling. This is a special case that further proves the need for the location-based forwarding policies described before. Indeed, from the point of view of the train ACS-GW, this access network has the same access unit as the 3.5 GHz 5GNR. The ACS-GW will use train location to differentiate when the gNodeB of the 5GMED Network is satellite backhauled. Let us assume as example that the 3.5 GHz 5GNR is backhauled with the satellite in the coverage area from km X to km Y. This coverage area is represented with a km range only for the sake of simplicity.

Table 10 describes the forwarding policies differentiation needed to recognize this situation. With this forwarding tables.

Service Flow	ACS-GW forwarding priority (from track point A to track point B)			ACS-GW forwarding priority (from track point B to track point C)		
	3.5 GHz 5GNR	**IEEE 802.11ad 70 GHz**	**Satellite**	**3.5 GHz 5GNR**	**IEEE 802.11ad 70 GHz**	**Satellite**
P1	2	3	1	3	2	1
P2	1	2	3	1	2	3
B1	2	1	-	1	2	-
B2	1	2	3	1	2	3

Table 10 - ACS-GW Forwarding Policy using the train position.

The interpretation that the ACS-GW will do of the table 10 for P2 is as follows:

- Both, P2 and B2 service will use the same forwarding policy between track point A and track point B.
- Service P1 uses the satellite as preferred technology, but its primary back-up will be different in each track zone.
- Service B1 will perform an automatic handover between 3.5 GHz 5GNR and 802.11ad 70 GHz when the train arrives at point B.

4.2.6 TAN segments

The number of ACS-GW units on the ground can be used to perform traffic engineering and obtain a geographical distribution of traffic (by national segments, or by international segments in different countries). This is relevant in a cross-border scenario, but also very useful in national scenarios on long distance lines or where the track topology is very complex.

A **TAN segment** will be defined as a track segment determined by absolute coordinates (latitude, longitude). Each TAN segment is associated to a **primary ACS-GW ground unit**.

Inside the TAN segment, the train ACS-GW ground unit initiates the corresponding IP/UDP tunnels terminating in this primary ACS-GW ground unit, as is described in section 4.2.2.1.3.

This situation is described in Figure 19. Initially, the train is located in TAN segment AB and the primary ACS-GW ground unit is the number 1.

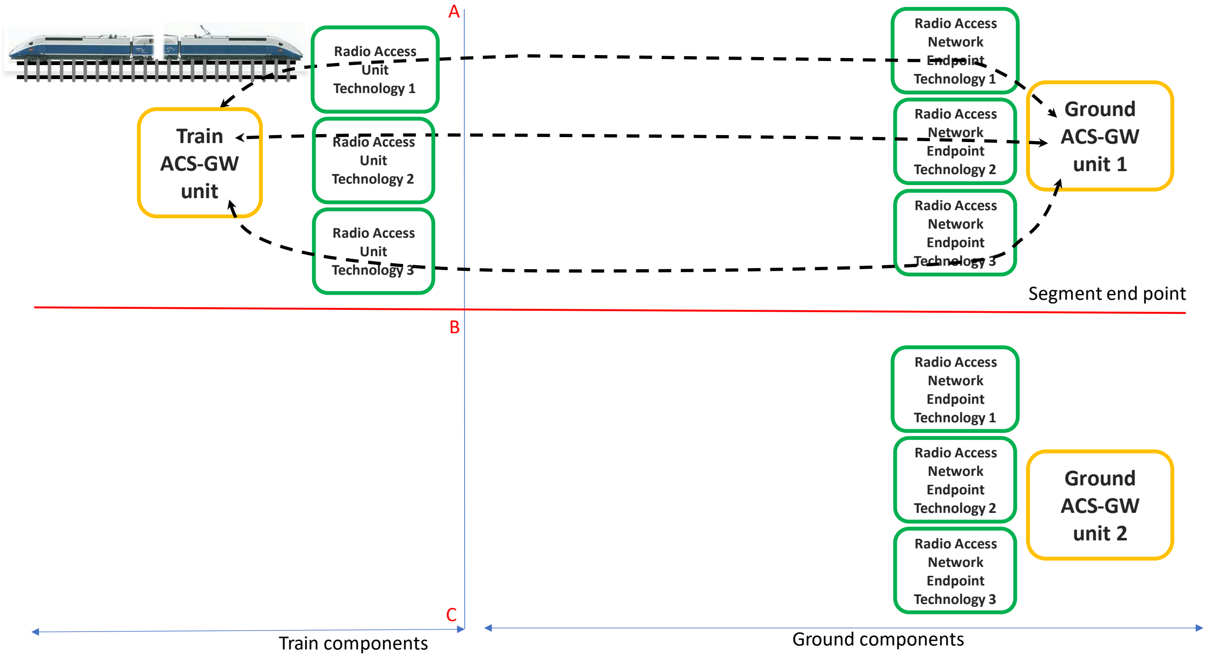

Figure 19 - Initial situation of the ACS-GW ground unit transition

A new set of predefined IP/UDP tunnels can be established between the ACS-GW train unit and a **secondary ACS-GW ground unit** (as in the primary unit case, one tunnel for each access network technology is defined). As the ACS-GW unis (train and ground) known the train geolocation information (including train position, speed, and train direction), the train unit will use these data to initiate this new set of IP/UDP tunnels before the train exits of the segment is located.

At this moment, two set of tunnels are established simultaneously: one between the ACS-GW train unit and the primary ACS-GW ground unit; other between the ACS-GW train unit and the secondary ACS-GW ground unit. Anyway, the set of IP/UDP tunnels used to forward the traffic of the services is the primary one.

This situation is described in Figure 20. The train has arrived at the point S, near the endpoint of the TAN segment AB. The primary ACS-GW ground unit is the number 1, but the secondary set of IP/UDP tunnels (blue coloured) is now established. To determinate the point S is a process that must be adjusted by the ACS-GW units (train and ground) according to the geolocation information. Currently, the method used to determine the point S is manual, and the explicit value is predefined in the configuration of the ACS-GW units (train and ground). The point S depends on the train direction.

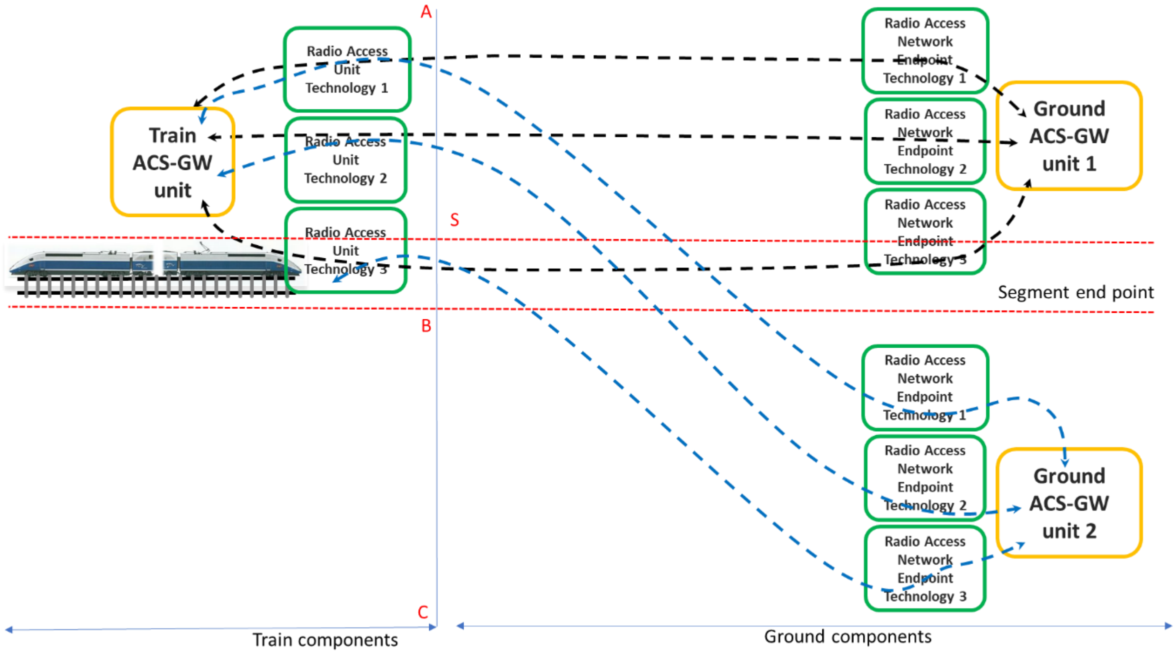

Figure 20 - Intermediate situation of the ACS-GW ground unit transition

Once the train reach the location that determines the end of the TAN segment, the ACS-GW units (train and ground) will use the new set of IP/UPD tunnels to forward the traffic and stop the connectivity check procedure (section 4.2.2.1.3.) over the old one.

In this way, the secondary ACS-GW ground unit is promoted to primary in this new TAN segment.

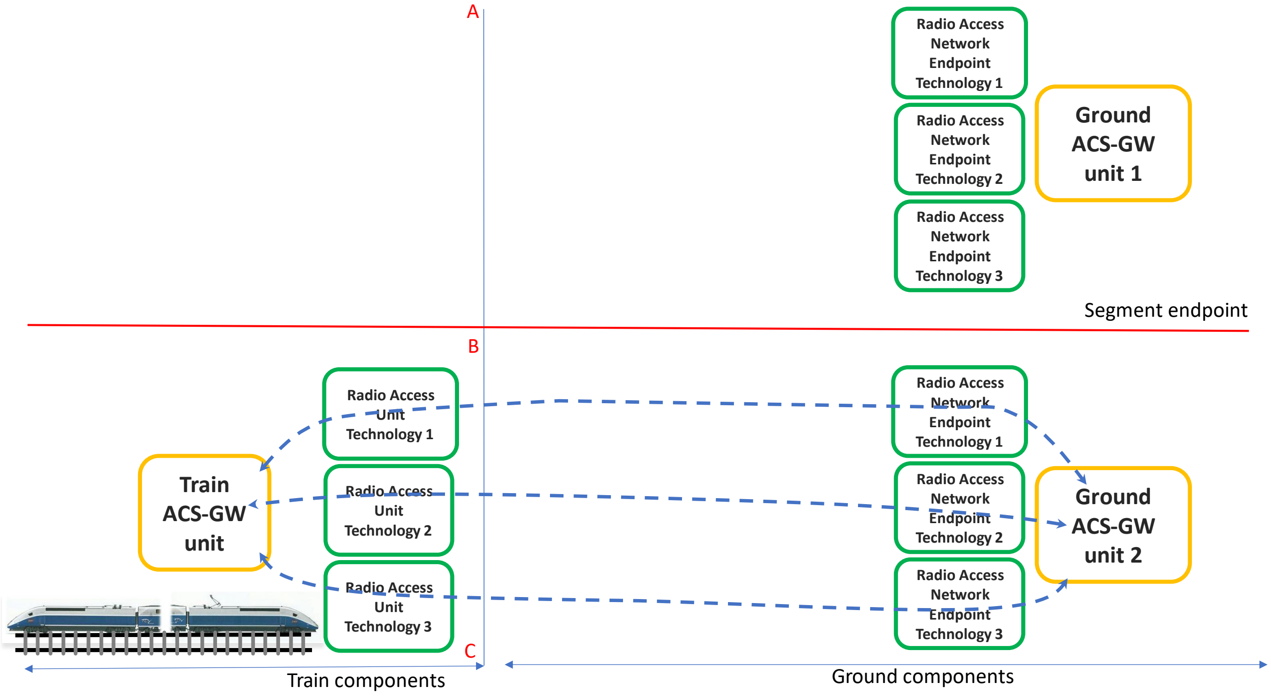

Figure 21 – Final situation of the ACS-GW ground unit transition.

Finally, Figure 21 illustrates the final situation. The train is now in the TAN segment BC. Ground ACS-GW unit has been promoted and now is the ground primary unit for the segment BC. The black set of tunnels are not used once the process is completed and are not used.

In this way, the transition between the primary ACS-GW ground unit in the first segment to the primary ACS-GW ground unit in the second service is completed.

Traffic directed to the train needs an additional consideration: the packets coming from a ground service component must be routed to the primary ACS-GW ground unit (serving the current location of the train). To do this, each ACS-GW ground unit must be able to forward packets to the rest of the ACS-GW ground units using the ACS-GW Segment Interface, described below. To avoid receiving packets of unknown provenance, the ACS-GWs ground units will maintain a list of valid IP addresses of all other ACS-GWs ground units with which it may interact in this way.[7]

To conclude this section, there is a remark about the satellite connectivity: the satellite delivers all the traffic in a centralized hub located in the Arganda Center (in Madrid). 5GMED Network will establish a connection with this hub. In this way, the satellite traffic can reach the ACS-GW ground Spanish unit. In case the train will be in France, the traffic directed to the train will be forwarded from the ACS-GW ground unit to the French one.

4.3 Railways Cross-Border Scenario Issues

This section contains a relation of all the identified cross-border issues related with the communication components. Note that there is another group of cross-border issues related to each specific service through the cross-border MEC interface, detailed in each subsection of section 3.1.2 for the UC3 services that uses this interface.

Some specific events must be considered in a TAN cross-border area:

- Roaming: as the train crosses the border, the 5G modem on-board will experiment the effects of the roaming process. The modem must change the frequency used by the radio interface and reconnect with a different 5G network. For this reason, the modem is configured to allow roaming.
- Vertical Handovers: As the coverage of the different radio access technologies may differ in both countries, this process must also be considered. As an example, in the 5GMED deployment, only the Spanish part of the corridor has 802.11ad 70 GHz coverage.
- Several ACS-GW ground units: the infrastructure of an international corridor will be composed of track segments managed by different railway infrastructure providers, possibly providing

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[7] The secure connection between two ACS-GWs in two countries can be done using the concept of Exposure Gateway platform presented in D3.3 [8]. However, this approach is presented as a theoretical approach that will not be implemented in 5GMED.

access to a different set of radio access technologies. This implies the use of several ACS-GW units across the corridor, managed by different administration entities. This process affects all the radio access technologies when moving across the border, even in the case they are using the same radio access technology at both sides of the border. In 5GMED project a different ACS-GW is deployed in each country to simulate this issue.

- Le Perthus Tunnel effect: Tunnels have specific regulatory issues about the spectrum to be used inside them that must be considered. Sometimes, the cross-border points for the track may be inside a tunnel (as in the 5GMED corridor case). Of course, the satellite coverage is also affected by the presence of the tunnel. Finally, the tunnel affects the positioning system of the train, as GNNS systems do not work inside.

A more complete description of the effects of these events is included in the following subsections.

Before this, it should be reminded that the ACS-GW manages the vertical handovers between radio access technologies, but the roaming process is established between the two 5G Cores. Both mechanisms are totally independent: the ACS-GW units are absolutely unaware of the roaming process between the 5G Cores, and the 5G Cores are unaware of the vertical handover between radio access technologies.

4.3.1 Effect of Mobile Network roaming in the services

The roaming architecture deployed by 5GMED for the 5G Network is explained in detail in D3.3 [8]. For our purposes, it will be enough to consider a simplified scenario: the 5G coverage near and inside the tunnel is represented in broad terms in Figure 22. In this figure, the blue area represents the French coverage, and the yellow area represents the Spanish coverage.

The tunnel coverage is considered part of the French mobile network (this is explained in D3.2 [7] because of regulatory issues). An overlap between the last cell in the tunnel and the first cell in Spain (at the exit of the tunnel) in insured for allowing roaming between the 5GMED French Mobile Network and the 5GMED Spanish Mobile Network.

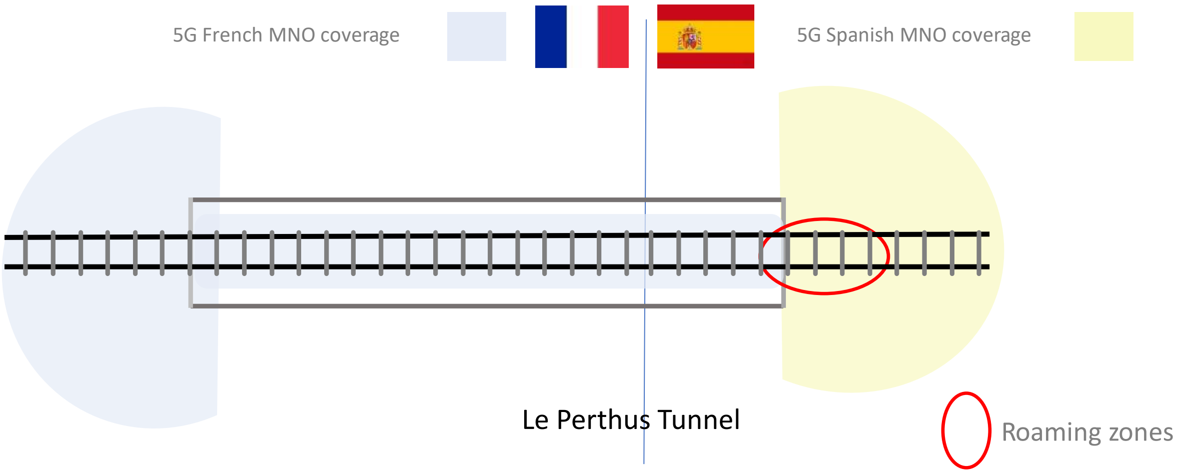

Figure 22 – 3.5 GHz 5GNR coverage in the cross-border and both sides of the tunnel

When the network roaming process starts, UC3 services will suffer an interruption in the connection. This will affect the services if the interruption time is larger than a given threshold (the service KPI with the same name defined in D2.1 [1]):

- 1 sec. for P1, P2 and B2
- 10 sec. for B1

Some service KPIs, as the service interruption time and the UL/DL packet reliability will monitor this situation and provide an exact idea about the impact of the roaming process.

4.3.2 Vertical handover effects

Figure 23 shows the coverage of the 802.11ad 70 GHz network (only deployed in 17 km., starting at the Le Perthus tunnel Spanish endpoint) and the satellite coverage. In addition, Figure 23 also depicts the possible Vertical Handover zones around the corridor from/to the 3.5 GHz 5GNR technology.

Depending on the ACS-GW forwarding policies (as was described i in the section 4.2.2.1.2) , when the train enters in these zones, a vertical handover maybe produced at service flow level.

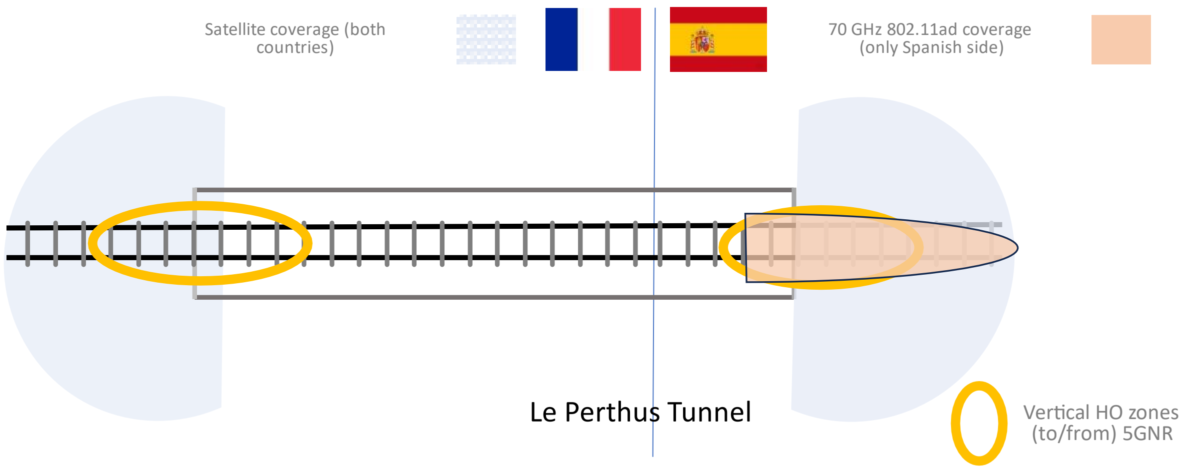

Figure 23 - Satellite and 70 GHz 802.11ad 3.5 GHz coverage around the tunnel.

Suppose the ACS-GW units of the trial are configured according to Table 8 used in section 4.2.5. In this case, the TAN behaviour in the French endpoint of the Le Perthus tunnel will be clear: All the train services will remain unaffected, except the P1 and B2 services that will experience a vertical handover between 3.5 GHz 5GNR and satellite (or the other way around, depending on the train direction). As this vertical handover will not be produced until the satellite is available, a seamless experience is expected at this point. However, service interruption time and the UL/DL packet reliability KPIs will demonstrate the results of this process.

On this side, according to Table 8, three different behaviours are expected:

a) Services that will experience the pure 3.5GHz 5G NR roaming effects: P2 service.

b) Services that will move from 70 GHz 802.11ad to 3.5GHz 5GNR or vice versa: B1. When the train crosses the border, it is supposed that the vertical handover process will be running in parallel with the 5G roaming process. Then, both effects will be experienced at the same time along a time interval. The best expected scenario is a seamless transition; the worse, a similar behaviour to a).

c) Services that will move from satellite to 3.5GHz 5GNR or vice versa: P1 and B2. The behaviour shall be similar to b).

Some service KPIs, as the service interruption time and the UL/DL packet reliability will monitor this situation and provide an exact idea about the impact of the Vertical Handover process in this area.

4.3.3 ACS-GW Cross-border issues

As explained in this section's introduction, more than one ACS-GW is needed to support an international scenario. Therefore, when a train crosses the border, the ACS-GW train unit must interact with a different ACS-GW ground unit. This will be enabled defining two TAN segments in the corridor separated by the border between France and Spain (see section 4.2.6).

As the traffic between the train and the ground is managed by the primary ACS-ground unit at each moment, the traffic will be home routed inside the respective countries: when the train is in Spain, the traffic coming/directed to the train is managed by the Spanish ACS-GW ground unit; when the train in in France, the traffic coming/directed to the train is managed by the French ACS-GW ground unit.

The secure connection between the ACS-GWs ground units in two countries to redirect the traffic between them can be done using the concept of Exposure Gateway platform presented in D3.3 [8]. However, this approach is presented as a theoretical approach that will not be implemented in 5GMED. Instead of this, according to the section 4.2.6, the French ACS-GW ground will only consider valid the IP addresses of the Spanish ACS-GWs ground unit to redirect the traffic (and reciprocally).

Some service KPIs, as the service interruption time and the UL/DL packet reliability will monitor the transition between ACS-GW ground units to provide an exact idea about the impact on the services of this process when the train cross the border.

5 Conclusion

After the analysis of the services composing each use case, D5.1 has established a set of requirements to be considered in the development of the service components. Also, a functional design consistent with the mapping of the use cases in the 5GMED architecture defined in D2.1 [1] is obtained.

This functional description is translated into a behavioural view of each service and a set of requirements to be satisfied by the service and communication components.

These, combined with the different design views, will allow to develop the necessary functions of the service components required to deploy the use cases in the testbeds, as well as defining the interfaces between them (that must be part of the content of next deliverable D5.2), with specific attention to the expected behaviour of the service flows in the cross-border areas and the process to validate and integrate the service in the testbeds.

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