FRANCO-GERMAN ECOSYSTEM
FOR PRIVATE 5G NETWORKS

5G-RACOM

Franco-German Innovation Project on 5G for Resilient and Green Rail Communications

Work Package 1: Use Cases, Requirements and Assumptions

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MINISTÈRE
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1 Executive Summary

This report summarizes the work and results of Work Package 1 (WP1), which is the basis for the 5G-RACOM project activities on FRMCS Spectrum Exploitation (in WP2) and Hybrid FRMCS Networks (in WP3). The target of WP1 is to motivate the project and clarify its scope and structure. Moreover, this document intends to provide a common basis on the general digital rail operation system including applications like voice, ETCS and ATO together with their QoS requirements as well as assumptions and a high-level architecture of the FRMCS. In addition to the generic introduction and description of digital rail operations and FRMCS, specific assumptions and requirements for the technical work in WP2 and WP3 are defined and described including details on the test environments. The whole document is complemented by relevant references on FRMCS and related topics.

2 Introduction

The European railway sector is envisioning a huge leap towards a digitalized train operation system, including a modernization of railway applications as well as the underlying communication system, which interconnects, e.g., the train with the infrastructure. France and Germany are pushing towards a highly efficient, reliable and automated railway system, which enables higher passenger capacity, increased train punctuality as well as enhanced energy efficiency, which in summary pays into a green European transportation system. With a large footprint in Europe, a close cooperation of the French and German railway industry and operators is of major benefit to develop the railway system evolution in accordance with the consumer needs and aims to create a momentum for the whole European railway system.

In this regard the harmonized and standardized European Rail Traffic Management System (ERTMS) [1] consisting of the European Train Control System (ETCS) and the cellular communication system GSM-R (Global System for Mobile Communications – Rail) [2] is further developed towards automated train operation (ATO) enabling highly as well as fully automated driving.

The advancing digitalization of rail operations comes with highly demanding connectivity requirements, e.g., regarding bandwidth and reliability. As the current 2G based railway mobile communication system GSM-R is not meeting those demands, the 5G based Future Railway Mobile Communication System (FRMCS) will be introduced [3], [4]. In addition, the FRMCS introduction is required due to the upcoming GSM-R obsolescence within the 2030s. The European railway telecommunications sector is making major efforts for developing FRMCS, e.g., within joint initiatives and projects such as 5GRail [5], Shift2Rail [6] and its successor Europe’s Rail Joint Undertaking (ERJU) [7]. A major design paradigm for FRMCS is the de-coupling of railway applications (e.g., ETCS, ATO) and the communication system (FRMCS) to reflect individual lifecycles. In addition, the usage of standardized off the shelf (COTS) technologies and components is targeted for enabling cost efficient products

Especially in France and Germany as large countries with the most extensive track network lengths in Europe, the deployment of FRMCS and its migration from GSM-R requires high efforts. A first step is made, with the EC (European Commission) having granted two railway mobile radio (RMR) frequency spectrum bands (at 900 MHz and 1900 MHz) for the deployment of FRMCS in European countries [8]. While the newly available 10 MHz bandwidth in the 1900 MHz spectrum can be deployed in addition to GSM-R for supporting the migration and reflecting the higher connectivity demands of future rail operation, its deployment comes with high efforts and costs. On the other hand, the 5.6 MHz bandwidth in the 900 MHz spectrum is already at least partially in use with GSM-R, making it challenging to be used by FRMCS in parallel without impacting the existing system.

At the same time, the standardization of FRMCS is driven forward by specification groups of UIC (International Union of Railways) and ETSI (European Telecommunications Standardizations Institute) within the Technical Committee for Railway Telecommunications (TC RT).

A major milestone in standardization will be (has been) achieved by finalizing the first version of FRMCS specifications, which are included in the Technical Specification of Interoperability (TSI) on Command, Control and Signalling (CCS) coordinated by ERA (European Railway Agency).

FRMCS v1 provides the general FRMCS architecture, the interface specification for “OB_APP” (the interface between onboard railway applications and FRMCS) as well as basic requirements, concepts and functionalities. While FRMCS v1 is seen as the fundament, FRMCS v2 is envisioned to provide the functionalities required for building and operating an FRMCS system. The functionalities required for interoperability are going to be tested in dedicated trails, while the final FRMCS v3 specifications are based on those verifications. In this context, 5G-RACOM already provides insights relevant for the FRMCS v2 specifications and may contribute to their verification.

2.1 About the 5G-RACOM Project

5G-RACOM stands for 5G for Resilient and Green RAil COMmunications and is an innovation project in the field of FRMCS introduction and will be delivered by the French and German group of partners led by SNCF Réseau (SNCF) and DB Netz AG (DB) respectively. The project has been established under the “Franco-German Ecosystem for Private 5G Networks” [9] program being set up by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) together with the French Ministry of Economics, Finances and Reflation/Revival (MEFR). This program funds several bilateral innovation projects on “Technical developments and application ecosystems for private 5G networks”.

Key premise of the project is that European railways will introduce 5G based FRMCS as a successor technology to GSM-R, with pilot deployments planned as early as 2025 [10].

The objective of the project is to investigate, develop and demonstrate key technologies to achieve a resilient, green and future-proof FRMCS system.

5G-RACOM has two major focus areas as shown below. These will be carried out almost independently in the French and German test environments by a subset of the project partners.

Spectrum exploitation in FRMCS networks

This focus area targets to exploit the available dedicated railway spectrum most efficiently by:

- Providing accurate channel models for railways as an extension of 3GPP models, based on channel sounding campaigns (for improving radio planning and deployments)
- Implementation and PoC of coexistence between FRMCS and GSM-R in 900 MHz based on white space and co-location approaches (for enabling more efficient deployments with 900 MHz only)

This project leg addressed in Work Package 2 (WP2) is coordinated by SNCF, with contributing partners Kontron Transportation France, IMT Atlantique, Siradel, Univ. Gustave Eiffel, Railenium, Funkwerk and DB Netz AG.

The coexistence trials should be performed in the 5GRail Test Area at Vigneux-sur-Seine, while considered options for channel measurement are not confirmed yet: Gare de Lyon, Paris; High-speed line LGV Est.

Hybrid FRMCS networks

The other pillar of the project addresses the extension of FRMCS towards additional spectrum as fallback and capacity enhancement by:

- Investigating hybrid network approaches with combination of private FRMCS and public 5G networks
- Implementing, evaluating and demonstrating multi-path solutions for parallel & seamless usage of both networks

This project leg addressed in Work Package 3 (WP3) is coordinated by DB Netze, with other involved project partners being Funkwerk, Kontron Transportation Germany, TU Chemnitz and TU Ilmenau.

The testing will be performed in the Digital Rail Testbed (DTB) of DB in the Erzgebirge region, Germany.

The overall project is organized based on four work packages as shown below. WP1 and WP4 are jointly led/coordinated by SNCF and DB Netze, WP2 is led/coordinated by SNCF and WP3 by DB Netze. Leads for sub-work packages and their partial tasks are typically assigned to other involved partner organizations.

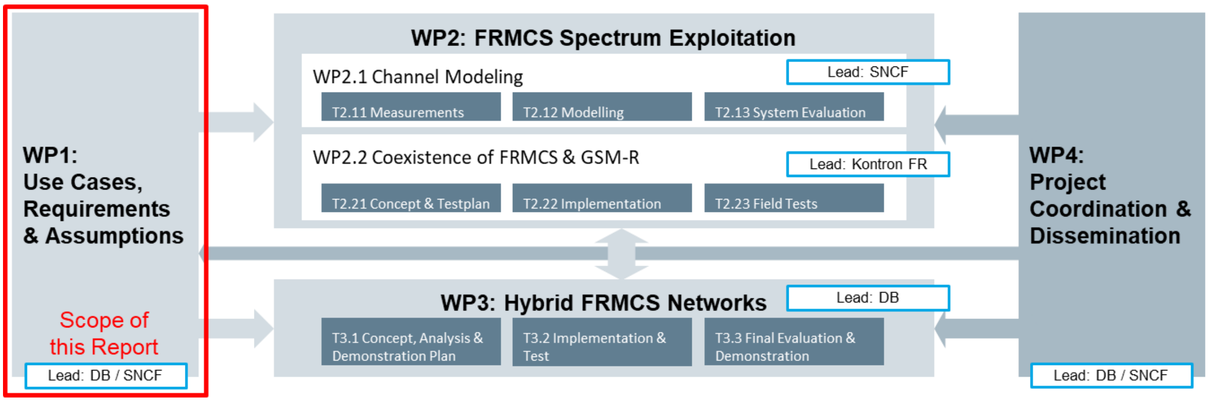

Figure 2.1: 5G-RACOM project organization

The project kick-off took place at the DB Netz AG headquarters in Frankfurt on January 10th, 2022. The project will run over 3 years until the end of November 2025. Milestones of (sub-)work packages and partial tasks are defined by the project time plan maintained by the SNCF and DB project leads. The project will conclude with a demonstration/show case and a field test report as final deliverables.

2.2 About This Report

This report is the first deliverable of the 5G-RACOM project and fulfils the objectives of the WP1 work package as shown in Figure 2.1. Chapters 2 and 3 provide a definition of the most relevant generic rail use cases and applications, together with their QoS requirements, which enable higher grades of automation for future rail operation. Also included are the generic assumptions and high-level architecture of 5G based FRMCS.

It also covers various design aspects of FRMCS to serve the requirements on connectivity in alignment with the current standardization status and further steps to be taken to make FRMCS ready for digital rail operation.

Beyond the deliverables of WP1, the report is the basis for the work in the subsequent work packages and therefore, chapter 5 also provides initial and very high-level scoping information for WP2 and WP3 to elaborate on.

This report was compiled by gathering relevant information based on the available literature including ongoing standardization activities and respective experience of the project partners.

3 Current and Future Rail Operation Applications & Their QoS Requirements

The future railway system is considered to develop towards increased capacity, quality and efficiency by deploying new and existing railway applications. In order to give a general and comprehensive overview, this section describes the most prominent applications which are of interest for future rail operation. A selection of those applications is considered for conceptual analysis and physical implementation in WP2 (see section 5.1) and WP3 (see section 5.2).

Denser train scheduling shall be achieved by deploying the European Train Control System (ETCS) with its progression towards APS (Advanced Protection System) based on the moving block concept as well as the introduction of automated train operation (ATO) systems with increasing Grade of Automation (GoA), as shown in Table 3.1 and described in detail in [11]. Especially for fully automated driving (GoA3/GoA4), additional systems will be introduced, with a whole set of new applications, e.g., based on automated incident prevention and management enabled by video transmissions [12]. Monitoring data transmitted via TCMS are also considered as potential application using FRMCS.

Grade of Automation	Description
GoA0: on-sight train operation	manual driving without safety system
GoA1: non-automated train operation	manual driving of the train, with basic train control support
GoA2: semi-automatic train operation	starting and stopping is automated, but a driver operates the doors, drives the train if needed and handles emergencies
GoA3: driverless train operation	starting and stopping are automated but a train attendant operates the doors and drives the train in case of emergencies
GoA4: unattended train operation	starting and stopping, operation of doors and handling of emergencies are fully automated without any on-train staff

Table 3.1: Overview on Grades of Automation

Rail operation applications are envisioned to be located onboard (within the train) and trackside (centralized as well as distributed).

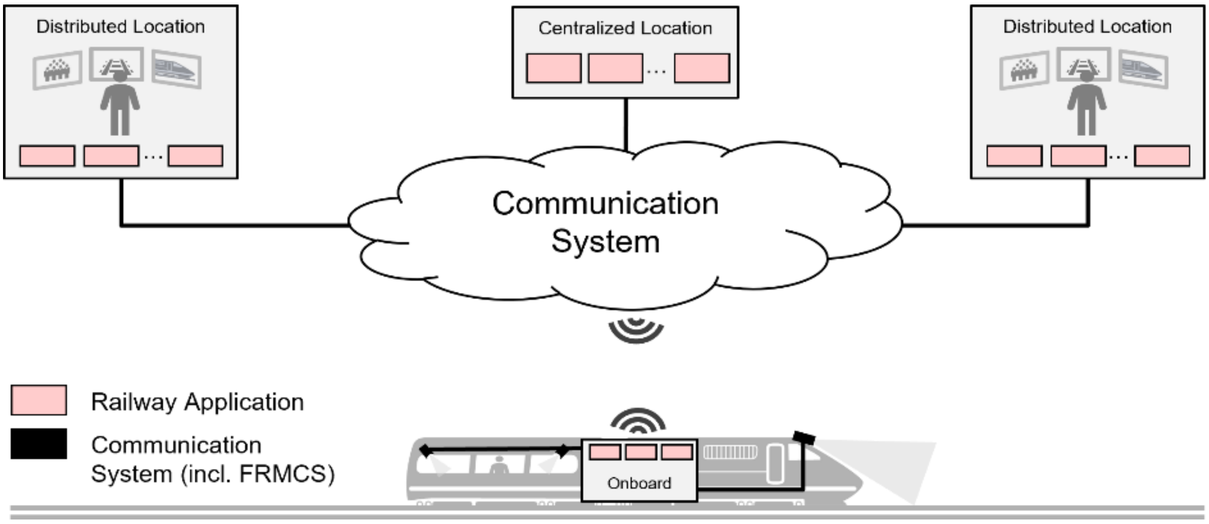

Figure 3.1: Overview of the Considered Rail Operation System

Within 5G-RACOM the most relevant rail operation applications are described to motivate the technologies under investigation in WP2 and WP3 as well as to provide a suitable picture of traffic demands as well as differences in the requested Quality of Service (QoS). For that purpose, the following subsections describe the rail operation applications Voice, ETCS, TCMS, ATO and video transmission (e.g., for remote driving or video surveillance), especially of interest for GoA3 & GoA4 operations. In addition, the last section focuses on the definition of relevant QoS requirements related to connectivity together with assumptions on application specific values.

3.1.1 Voice

Voice is one of the main applications utilized nowadays via the current GSM-R network. Voice calls in railways can be point to point as well as group calls and include various roles of railway personnel, e.g., train drivers, train staff as well as dispatchers, controllers or emergency managers located at the trackside. Voice calls are established typically only in special situations with the need for clarification among the participating parties. The railway voice communication comprises several additional features, e.g., functional and location dependent addressing, arbitration and messaging. In emergency situations, the railway emergency communication (REC) is used by establishing a high priority voice group call together with an emergency alert. Even though voice is relevant also with higher grades of automation (e.g., for communication in incident and emergency cases), its portion on the overall rail operation communication is assumed to be reduced and more and more replaced by data-based communication.

3.1.2 European Train Control System (ETCS)

The purpose of the European Train Control System (ETCS) is to ensure the safe operation of train traffic. For that purpose, the rail track is sub-divided into rail segments (blocks), while only a single train is permitted to be located within a single block. In order to give permission for a train to enter a new block, a Movement Authority (MA) message is transmitted from a trackside Radio Block Centres (RBCs) to the train [13]. The MA calculation is among others based on information from multiple trains obtained e.g., via position reports that the train frequently transmits towards the RBC. The position reports include information such as front/rear-end position of the train, speed, etc. Future rail operation is targeting to reduce train headways by utilizing the moving block approach with more frequent transmissions of MAs. The progression of ETCS towards APS (Advanced Protection System) is not only covering the moving block approach but also combines RBC and interlocking in a single system.

RBCs can be deployed in a distributed fashion, where each RBC is responsible for a unique geographical region of the infrastructure managers (IM) rail track system. In case a train moves from one region to another, an RBC handover needs to be performed. While in GSM-R CSD (Circuit Switched Data) a make before brake behaviour is realized with two modems (each connected to an RBC), the FRMCS architecture targets to realize RBC handovers with a single modem, like in GSM-R PSD (Packet Switched Data). Note that the special case of border crossing (switch between networks of two countries) is not specified for FRMCS at the point in time this report is written.

ETCS is considered to be categorized as safety-critical application. Even though the safety aspect is addressed by a dedicated safety-layer within the application, which is decoupled from the communication functions, it should be noted that ETCS data might not be allowed to be transmitted via public 5G networks (based on national regulations). An exception might be fallback cases where no FRMCS is available. Note that public 5G networks might also be used as redundant connection of rail track equipment, such as switches or signals, in addition to the fibre network connection.

The Quality of Service (QoS) requirements for ETCS listed in section 3.1.6 are assumptions based on available QoS references for ETCS over GSM-R [14], which to some extend is assumed to be applicable for ETCS over FRMCS and early considerations on FRMCS QoS requirements [15], [16].

3.1.3 Train Control and Monitoring System (TCMS)

The train control and monitoring system (TCMS) is mainly an onboard system used to control and monitor a set of train equipment and functional processes [17]. Based on a control and monitoring architecture, the TCMS centralizes all information about the operational status of relevant train equipment. The systems and functions to be controlled or monitored can range from the temperature in the passenger compartment to doors, breaks or the traction system of a train. The data collected at the onboard is transmitted via train-to-ground connectivity towards the TCMS trackside [18]. Apart from voice, ETCS and ATO systems, the TCMS trackside is not operated by a railway infrastructure manager but usually by a railway undertaking (RU). Hence, the communication from the onboard TCMS terminates in the domain of the train operator. In consequence, the TCMS application is here not assumed to be a “rail operation” application but rather an “RU application”. The assumptions on QoS requirements related to connectivity for TCMS listed in section 3.1.6 are derived based on [18].

3.1.4 Automatic Train Operation (ATO)

The implementations of GoA2-GoA4 operation are based on the rail operation application ATO (automatic train operation), which is based on “Journey Profiles” including information about the driving behaviour of the train [19]. Journey Profiles are transmitted from the centralized ATO trackside system to the train. While the MAs for ETCS indicate the permitted driving behaviour, the Journey Profiles inform about the intended acceleration and breaking. Since the content of Journey Profiles can be influenced by the behaviour of other trains it is assumed to be semi-frequently updated, even though the update frequency is assumed to be below the one for MAs. The ATO trackside system gets information from the train via the status report, referencing the train’s position to the rail segments. The automation functions rely on up-to-date segment profiles and maps including descriptions of the relevant rail segments. At the beginning of the journey, the train obtains the latest version of all relevant segment profiles (i.e., maximum speed, temporary limitations, curves, etc.) and journey profiles, which will be traversed during the journey. In addition, it can happen that relevant updates become available while the journey has already started or there is a change in the journey, which requires the download of further segment profile data. The assumed QoS requirements on connectivity listed in section 3.1.6 are derived based on information within [15], [19], [20] and [21].

3.1.5 Video Based Remote Operation

Especially in rail operations with higher Grades of Automation, video becomes a crucial component, e.g., for the management of incident situations. In cases, where the automated incident management system is detecting a potentially critical situation, which requires the involvement of a human authorized user (e.g., incident or emergency manager), video needs to be transmitted from the train’s onboard cameras towards a trackside incident or emergency management centre, where a remote human can assess the situation based on the transmitted video [22], [23]. It is assumed that the train is equipped with a variety of onboard cameras observing specific areas inside and outside the train, e.g., interior camera, door camera, front/side/rooftop camera, while the number and type of cameras might vary based on the train type (e.g., freight train, regional train, high-speed train).

Multitude of video streams from several cameras is assumed to be transmitted in parallel in order to give the human remote staff the opportunity to assess the situation from several perspectives, which might lead to specific actions, influencing the further train operation. The remote assessment of the potentially critical situation based on video streams from onboard is referred to as remote vision or remote supervision.

In specific situations, the train might need to be controlled from remote, e.g., door closing in embarkation situations or even remote driving. In the latter case a remote driver is steering the train based on onboard video, which is considered to apply to low speeds only.

The quality of video for remote operation is currently not specified. In this project, the data rate per video stream is assumed as up to 3.5 Mbps [22]. For remote driving it is assumed that at least 2 parallel video streams are required (far view and close view) [23]. For remote supervision it is assumed that a higher number of parallel video streams is requested, while the quality/resolution is expected to have lower requirements compared to remote driving. In summary, the uplink video data rate for remote supervision is expected to range between 1-10 Mbps. Apart from the pure video transmission in the uplink, remote operation also considers control data for the downlink, e.g., for steering the cameras or controlling the train movement.

3.1.6 QoS Requirements

The earlier sections have introduced the basic traffic behaviour for the applications of interest. In this section more specific characteristics on the required end-to-end (E2E) connectivity and its expected performance shall be defined based on relevant Quality of Service (QoS) key performance indicators (KPIs). The actual values required by the dedicated applications are derived based on the references mentioned in the specific application sections.

Before the actual numbers are introduced in a common table, the characteristics and KPIs are explained.

Transmission Type

Describes the fashion of the data exchange. It can be audio or video streaming, or messages based on data transmission.

Occurrence

Describes the frequency when the transmission is happening. It can be occasional (e.g., based on events like mission start), frequent or semi-frequent.

Direction

Shall indicate if the traffic is uplink (UL), downlink (DL) or both directions (UL+DL).

Data Rate

The number of bits transmitted per second (end-to-end incl. L3+ headers).

Packet Latency

The delay between transmission of the first bit of a L3 packet (at originating application) and reception of the last bit of the same L3 packet (at target application).

Packet Reliability

The number of L3 packets successfully transferred (end-to-end, i.e., from application to application) within the required packet latency.

Application	Transmission Type	Occurrence	Direction	Data Rate	Packet Latency	Packet Reliability
Voice	Audio Stream	Occasional	UL+DL	24 kbps	100 – 500 ms	99 %
ETCS	Messages (Position Report)	Frequent	UL	4 – 10 kbps	100 – 500 ms	99.9 %
	Messages (Movement Authority)	Frequent	DL	4 – 10 kbps	100 – 500 ms	99.9 %
ATO	Messages (Journey Profile)	Semi-frequent	DL	1 – 100 kbps	100 – 500 ms	99.9 %
	Messages (Segment Profile)	Occasional	DL	1 – 10 kbps	100 – 500 ms	99.9 %
	Messages (Status Report)	Frequent	UL	1 – 10 kbps	100 – 500 ms	99.9 %
TCMS	Messages	Occasional	UL	1 – 100 kbps	500 ms	—-
Video based Remote Operation	Video/Audio Stream for Remote Driving	Occasional	UL	1-7 Mbps	100 – 200 ms	99 %
	Control Data	Occasional	DL	10 – 100 kbps	50 – 100 ms	99 %
	Video/Audio Stream for Remote Supervision	Occasional	UL	1 - 10 Mbps	100 – 200 ms	99 %
	Control Data	Occasional	DL	10 – 100 kbps	100 – 200 ms	99 %

Table 3.2: Assumptions on requirements for selected rail operation applications relevant for up to GoA4. Content of the table is compiled based on the references and explanations given in the sections above.

4 Generic FRMCS System Assumptions and High-Level Architecture

Rail operation applications, use cases and its requirements have been analysed by UIC and compiled in the documents [24] and [25] (including the applications of the previous chapter). The resulting FRMCS use cases, system principles and functional requirements have been covered in 3GPP Technical Specification [26], and Technical Report [27] while a generic FRMCS architecture has been studied and presented in the ETSI TR 103 459 [28].

The high-level system architecture defines application stratum, service stratum and transport stratum (see Figure 4.1), while the latter two constitute FRMCS. The service stratum includes functionalities like identity and role management, security features, service session management and group communication services, while the transport stratum provides connectivity based on the indicated Quality of Service (QoS).

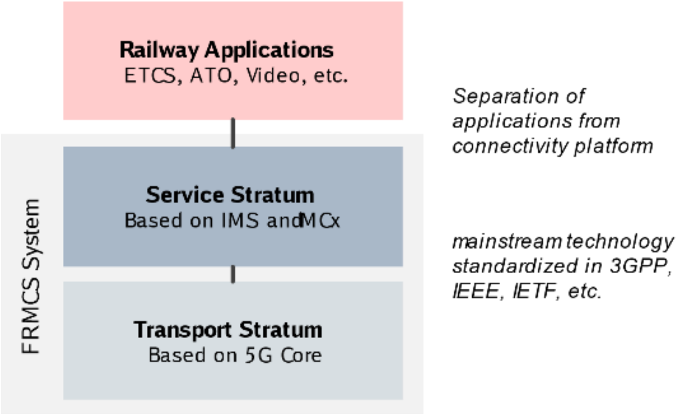

Figure 4.1: High-level FRMCS overview

As stated in [28], service stratum functionality is envisioned to be implemented via the Mission Critical services (MCX) framework on top of the 5G system specified by 3GPP. MCX has its origin in public safety verticals, while railway industry substantially contributed to further evolutions to reflect its own requirements. A preliminary study on the architecture of FRMCS in 3GPP (including MCX) can be found in [29] and [30], further are included in [28]. Note that at this point in time it is assumed that any traffic transmitted via FRMCS needs to be handled via MCX.

The FRMCS transport stratum concept includes multi-access and multipath capabilities. Multi-access is referring to a radio access technology (RAT) agnostic approach, assuming 3GPP 5G core for coordinating the utilized RATs. On the other hand, multipath is referring to the usage of multiple networks (each with a dedicated core network) simultaneously.

It is assumed that the FRMCS trackside network is owned and operated by the infrastructure manager (IM), in this case DB or SNCF. FRMCS onboard system is assumed to be operated by the respective railway undertaking (RU), while the IM is able to provide specific configurations for the onboard system, the so-called FRMCS profile for increasing service quality in dedicated scenarios, some railway applications might be allowed to additionally utilize public 5G networks. In these cases, the multi-connectivity functionality of FRMCS provides the option to route data traffic between a train and trackside application via two or more parallel user equipment (UEs). More details on the assumed FRMCS architecture are illustrated in Figure 4.2. The functionality for employing multiple UE connections is integrated in the FRMCS Onboard Gateway at the train side, while the need of a corresponding functionality at the trackside is assumed to be subject to a particular solution.

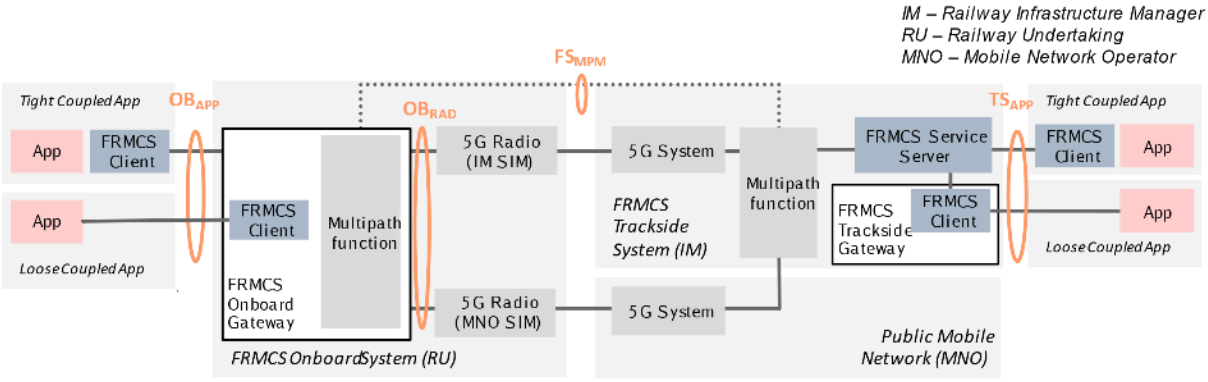

Figure 4.2: FRMCS architecture example (based on [28]), including the indication of the operators: railway undertaking (RU), infrastructure manager (IM) and mobile network operator (MNO).

For the underlying FRMCS infrastructure, the deployment of the cellular communication system as well as the radio spectrum are relevant for assumptions on the supported data rate. The target spectrum for rail operations in Europe is a 5.6 MHz band at 900 MHz (currently partially used for GSM-R) as well as a 10 MHz band at 1.9 GHz. The current available GSM-R spectrum slightly differs among European states, while in Germany the 4 MHz Band 876-880 MHz (uplink) and 921-925 MHz (downlink) is reserved and used for GSM-R, while 873-876 MHz (uplink) and 918-921 MHz (downlink) is usable for railways as well [31]. Here it is assumed that some of the radio towers of the current GSM-R can be used for FRMCS as well, while additional radio tower constructions might be required. For the 900 MHz spectrum and rural areas an average inter-site distance (ISD) of 8 km (4 km for the 1.9 GHz band), and for urban areas an ISD of 4 km (2 km for the 1.9 GHz band) is assumed.

5 5G-RACOM Project Scoping in WP2 and WP3

5.1 FRMCS Spectrum Exploitation

Unlike GSM-R radio, 5G NR (New Radio) is quite sensitive to interferences from other radio sources in neighbouring frequencies. To maintain the level of interferences as low as possible, understanding radio propagation in railway environments is key.

In the first part of the FRMCS Spectrum Exploitation package, the efforts will start with a focus on measuring the quality of transmission and reception with embedded equipment when a train is passing by a fixed antenna. This is what is called the radio channel. This exercise will be achieved in several railway environment that are of particular interest, like urban and high speed, but have not been defined yet.

The European Commission granted 2 frequency bands for FRMCS deployment and operation in the 900 MHz and the 1900 MHz. Those 2 frequency bands have different characteristics, yet complementary for a railway usage. Radio propagation is better at 900 MHz than at 1900 MHz, hence allowing wider spacing between base stations, the main radio infrastructure along the tracks. However, because of the increased spectrum available for railways, the 1900 MHz brings better throughput capacity when the base stations are narrower spaced.

From a radio perspective, railway environments are complex. The quality of radio links ensures the good performances of the FMRCS network. It is then essential to know the characteristics of such links to optimize deployments, especially for the 1900 MHz band.

Propagation models available today are not suitable for railway applications, therefore the railway community needs to create its own models of propagation channels. In doing so, a first step consists in launching an ambitious campaign of measurements in different railway environments like high speed, urban or open trenches. Such measurements can be achieved with the help of channel sounders. A complex analysis of that amount of collected data will enable the definition of propagation characteristics leading to brand new railway radio channels. This analysis will also allow for improvements of the existing predictive models that are based on digital twins. As soon as the channel models are defined, they are to be fed into digital platforms that simulate railway operation, more specifically the radio part of FRMCS.

Having a better understanding of propagation characteristics in the 900 MHz band is not going to be enough during the migration period. Indeed, in the initial deployment phase of FRMCS, the GSM-R will still be in operation.

On one hand, FRMCS deployment in the 900 MHz band represents a great opportunity to optimize existing infrastructure’s usage. On the other hand, it is going to be essential to evaluate performances and operational conditions for the coexistence of both GSM-R and FRMCS within the same 900 MHz band.

Such coexistence can be of two types:

1. First solution consists in overlaying FRMCS and GSM-R within the same 900 MHz band. This allows the two networks to access and use the full 5,6 MHz of available bandwidth thanks to smart scheduling of the time/frequency resources towards the railway undertakings.
2. Second solution divides the 5,6 MHz available bandwidth into two smaller sub-bands (not necessarily of the same size). Then, each network will separately operate in the sub-band that it has been allocated to.

5.1.1 Channel Sounding and Channel Modelling

5.1.1.1 Why Do We Need New Channel Models?

Railway environments are very complex and harsh from a radio point of view (see Figure 5.1). Various obstacles such as pylons supporting the catenary and rapid transitions between different scenarios (cutting/tunnel, cutting/viaduct) can create severe radio impairments. In fact, due to its high-speed, the train can rapidly go through diverse scenarios and a single model is unable to accurately capture the channel variations. Thus, environment transition must be considered in the railway propagation channel models, as well as transition phases between line-of-sight (LoS), non LoS or obstructed LoS conditions. In addition, Doppler effects and possible interferences due to the proximity of high voltage (catenary) in the vicinity of the antennas render the railway environments very specific compared to the urban or suburban environments generally considered today in standardization groups (3GPP). For all these reasons, the 5G-RACOM project will develop realistic 5G railway radio channel models enabling FRMCS evaluation to anticipate and facilitate wide FRMCS deployment in the railway frequency bands not covered in other 5G related projects.

Figure 5.1: Examples of railway environments

Radio channel sounding measurement in railway environments is a very challenging task. Various issues must be considered or solved when planning the measurements: cost and availability of measuring trains, insertion among normal traffic, installation of temporary base stations along the tracks and of antennas on the train and development of sounding techniques for high-speed with a large memory size for data acquisition. 5G NR based FRMCS deployment in Europe, represents 150,000 km of railway lines where GSM-R is installed and only 23,000 km are high speed line (HSL). Currently, to the best of our knowledge, there is no model of 5G radio channel [32] in the railway frequency bands (RFB) harmonized at European level. In other words, 5G railway radio channels in 900 and 1900 MHz bands are not yet characterized and it requires further study.

The development of radio channel models is an active field of research for 5G NR standard. They generally give an analytical or stochastic expression of the channel impulse or frequency response obtained thanks to measurements or may rely on deterministic ray tracing tools. Trends on channel models for 5G are presented in [33]. A very complete state of the art on existing railway channel models is provided in [32], which highlights the crucial lack of usable existing MIMO (Multiple Input Multiple Output) radio channel models for 5G particularly in the Railway Frequency Bands. The ambition of 5G-RACOM project is to fill this gap. In order to develop complete 3D channel models for FRMCS, wideband dual-polarization MIMO measurements in the RFB will be carried out in the 5G-RACOM project to extract measurements based statistical MIMO channel models. Two complementary Channel Sounder Systems (CSS) will be considered in a complementary manner.

Railway environments are generally very different than the ones considered for cellular systems or in other transport modes (automotive, maritime and aeronautical). They also differ depending on the train category. In general, four main categories are considered: urban, regional, intercity and high speed. The profile of HSL is generally linear with large curvature radius. Classical HSL environments are open spaces, cuttings, viaducts, tunnels and stations. In [34] the geometry of all these environments is described. The speed is generally 300 or 320 km/h, thus from a radio point of view, channel models should consider non-wide-sense stationarity, rapid time-variability and large Doppler shifts caused by the high speed of the train. Intercity lines or regional lines are mainly deployed in rural environment that can be open area, where it is possible to cross open field, forest, mountains, suburban areas, medium size tunnels, etc. The highest train speed is generally around 180 km/h. Areas with a lot of pylons and catenaries can be encountered near big cities or marshalling yards. Metro or urban line are generally deployed in underground environments. The type and size of tunnels will vary depending on the line (old or new). The highest speed is generally around 60-80 km/h, but it can be up to 110-120 km/h for some lines.

The development of channel models for railways is a very active research field in recent years, particularly for HSL and metro. The scenarios for train communications vary between Train-to-Ground (T2G), Train-to-Train (T2T) and intra-train communications. A literature analysis shows that most of the scientific papers on the topic are dealing with radio propagation models. They mainly present narrow-band parameters such as path-loss, fading characterization, angle distribution statistics and, sometimes, the delay distribution. In [35], the authors have classified several existing papers dealing with radio channel characterization mainly in HSL environments. The measurements are generally performed over 20 MHz in the LTE band. The measurements-based models proposed are mainly simple TDL (Tapped Delay Line) or CDL (Cluster Delay Line) models generally with no geometric information on angle of arrival or departure of the rays.

5.1.1.2 MIMO Channel Sounding Methods/Techniques

Channel sounders will measure the different channel coefficients of the MIMO channel. They differ in the excitation signal and in the processing methods at reception (switching between antennas or parallel processing [36]. Here we describe some MIMO channel sounders that operate around 6 GHz and support mobility. The four main types of probes that meet these criteria are: MIMOSA [37], RUSK [38], Propsound [39] as well as sounders built from software defined radio cards [40].

The RUSK sounder developed by Medav considers a single radio frequency (RF) chain at both transmit and receive sides. It operates at 300 MHz, 2 GHz and 5 GHz with a maximum bandwidth of 240 MHz. The maximum possible speed for measurements is 338 km/h. The sounding signal is a pseudo-random binary sequence with time division multiplexing (TDM). The complex CIR of each link are obtained by switching between the transmitting and receiving antennas and correlating the received sequence with the known transmitted sequence at the receiver.

The Propsound sounder developed by Elektrobit also uses pseudo-random binary sequence and TDM probing and antenna switching. The CIR of the elementary channel of the links is obtained by correlation. This sounder operates between 1.7 and 5.9 GHz with a maximum bandwidth of 200 MHz. The maximum speed supported depends on the number of antennas used. A railway scenario in SISO (Single Input Single Output) was performed at 240 km/h.

Channel sounders built with software defined radio cards are becoming more and more common. The excitation signal is often a Frequency Division Multiplexing (FDM) or Time Division Multiplexing (TDD) LTE signal. They usually have as many RF chains in parallel as there are transmitting and receiving antennas. The CIR is obtained by estimating the classical channel by considering the pilot symbols of the LTE frame. The sounder characteristics depend on the performance of the software radio cards used. The maximum operating speed depends mainly on the position of the pilot symbols in the signal, which thus determines the maximum Doppler frequency supported by the system.

In the 5G-RACOM project, we will consider two different Channel Sounding System (CSS). Firstly, it will allow us to split the measurement and modelling effort between two different teams considering the scenario conditions and matching to CSS performances. Secondly, this will permit to perform multi-band (eventually simultaneous) measurements. Dividing the scenarios makes it possible to share the burden of the experimental task between the collaborators on the one hand and to have several measurement results simultaneously in a shorts time on the other hand. The multi-band measurements allow to compare the channel performances obtained in each band, thus drawing certain conclusions about the channel modelling for a given band as well as which band is preferred for which scenarios. Note that each channel sounder has its own characteristics and limitations. These should be considered when assigning the identified measurement scenarios to the CSS. The IMT Atlantique CSS will allow to measure geometrical information thanks to the use of specific antenna arrays but only if these special antennas can be installed on the train.

In France, trains are running in various environments, thus a same train often encounters different environments during a single trip. SNCF would like to focus mainly on five specific environments, considered as particularly complex from a radio point of view: A High-speed line, probably between Paris and Strasbourg; a dense urban area, probably the one crossed by the railway lines arriving at Gare de Lyon in Paris; a large railway station, probably Gare Montparnasse in Paris; a tunnel area; and a hilly railway line. Given the feasibility and costs constraints, arbitration will be necessary between these 5 environments.

Two channel sounders considered in the 5G-RACOM project are described in the following chapters.

5.1.1.3 Channel Sounders Considered in the 5G-RACOM Project

5.1.1.3.1 IMT Atlantique Channel sounder

IMT Atlantique has been developing a versatile measurement equipment to study wireless propagation channel for several years. On the transmitter part, an arbitrary waveform generator is used to produce a wideband and periodic signal. Switched antenna arrays are used to investigate direction of arrival of the propagation channel. This method is cheaper than using several transmitters/receivers and simplifies the calibration procedure. However, it takes more time to measure and usually requires periodic transmitted signal. This technical is only possible if the scanning rate is fast enough compared to environment variations. On the receiver part, a software defined radio (SDR) architecture was chosen to provide flexibility. The 160 MHz instantaneous bandwidth, which is acceptable for research on existing systems, is smaller than other dedicated channel sounders. The Figure 5.2 presents main characteristics and a picture of a measurement setup.

SDR based (X310)
Carrier : 50 MHz – 6 GHz
Bandwidth : Up to 180 MHz
MIMO capability
Portable RX : 13 kg / 150 W

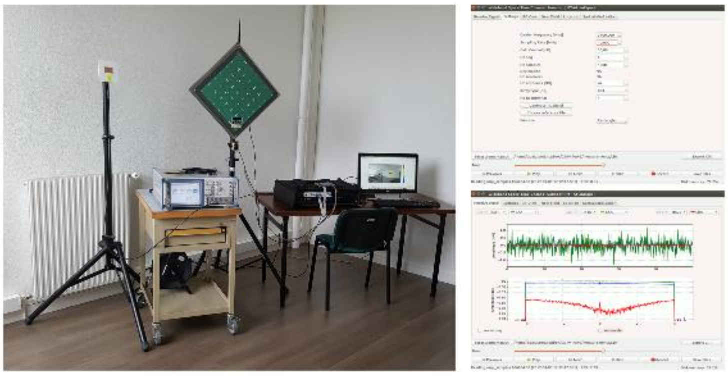

Figure 5.2: Main specifications capacities

According to its architecture, this equipment is very flexible to fit the need of each research study. For instance, it was successfully used to estimate the direction of arrival at the base station, using a 64 dual polarization antenna array [41]. A real time demonstration is given in the video [42]. The equipment was also modified to investigates the capability to estimate direction of arrival of Wi-Fi users [43] with a switched antenna array. Even if the transmitted signal is not periodic (Wi-Fi standard), it was demonstrated that direction of arrival estimate was possible by adding a phase recover technique at the receiver. An example is given in the Figure 5.3.

Figure 5.3: 3D directional of arrival estimate of Wi-Fi devices

This equipment has been updated to make a proof of concept of spatial modulation [44]. A live demonstration was performed in 2017 during the International Conference on Communications. The full setup is described in the video [45].

The last example of equipment capabilities is about 5G. Several dedicated antenna arrays were developed to investigate direction of arrival at the mobile. Some antenna array prototypes are depicted in the Figure 5.4. A dedicated algorithm was also developed to estimate directional of arrival while the car was moving [46].

Figure 5.4: Examples of mobile antenna arrays developed in previous projects

All this measurement experiences (hardware and software tools) will be the strong basis to define and setup 5G Railway channel measurements, necessary to investigate MIMO railway channel models.

To support MIMO simulation, 5G channel models include spatial properties (Geometrical Spatial Channel Models or Directional Tapped Delay line models for instance). For that purpose, direction of arrival has to be estimated during measurements and requires the use of antenna array. The number of antennas is very important because it is directly related to the angular resolution. Thus, the antenna configuration on the train will be very important.

Two sounders are available in the project and results should be as complementary as possible. The other channel sounders will use a dedicated transmitter with wider bandwidth. It will be very fruitful to study specific configuration. However, the number of measurement configurations will be limited. To be representative, channel measurements should be performed at the same frequency using a transmitted bandwidth larger or equal to the system bandwidth. Unfortunately, these future FRMCS bands are already used, and the surrounded spectrum is overload. Instead of using a dedicated transmitter, IMT Atlantique propose to use existing mobile base stations. As you can see in the Figure 5.5, many base stations from different operators are available along railway tracks. This approach offers many advantages: same frequency band, realistic configuration, wide range of configurations, no transmitter to deploy, reference and known signals available…

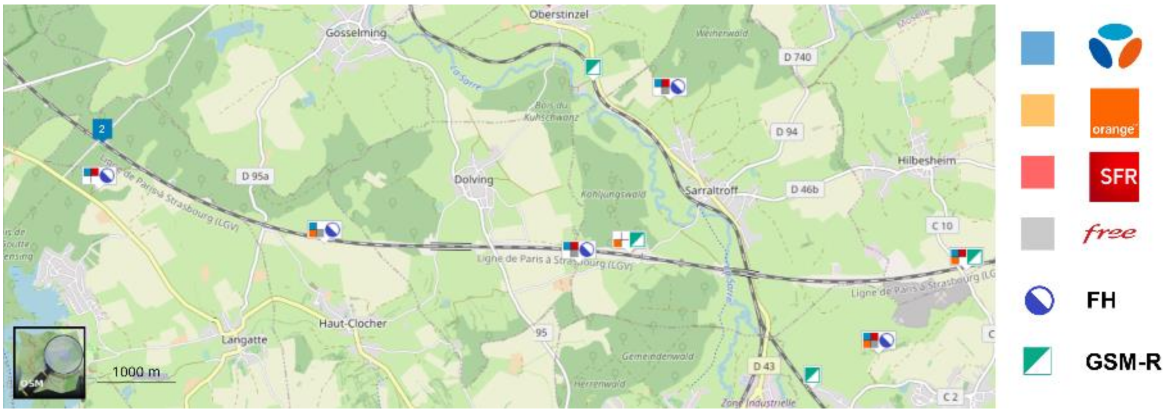

Figure 5.5: Example of available transmitters along LGV Est

However, these is also some drawbacks. Transmitter characteristics are not so accurate. For instance, precise antenna pattern, transmitted power or physical cell id are not available in the ANFR data base. The quality of channel measurements may be reduced because the reference signal can suffer from inter and intra cellular interferences. At last, such approach will generate a large amount of data and a much more complex post processing.

5.1.1.3.2 Railenium / Uni. Eiffel Channel Sounder

Railenium will use the Uni. Eiffel's channel sounder. It is a sub-6 GHz 4x4 MIMO reconfigurable channel sounder based on SDR (Software Defined Radio) boards (USRP 2954R from National Instruments) derived from [40]. The system is a combination of hardware and software modules. Figure 5.6 gives a photography of the system. The sounding system is based on the estimation of the channel frequency response using known transmitted pilot signals.

The hardware part of the sounder consists mainly of SDR boards, controlled by host computers. SDR allows reconfigurability in terms of frequency, input/output power, sampling rate. The system is controlled with LabVIEW software. The excitation signal is an OFDM modulated signal with a 20 MHz bandwidth. The structure of the signal is identical to an LTE-TDD signal in terms of number of subcarriers, frame duration, and number of slots. Both transmitter and receiver sides are synchronized with a specific clock distribution based on GPS signal. Rubidium clocks can be used if GPS is not available.

On the receiver side, the main function of the system is to detect the frame timing and to estimate the radio channel complex frequency response (CFR). The main characteristics of the channel sounder are given in Table 5.1. The CFR are recorded continuously. The sounder can record data for 1 hour and it is designed to operate at high speed [47]. The host computers on both sides provide a user interface where the user can set the RF (Radio Frequency) parameters, start the system, and display the CFR and its inverse Fourier transform, the channel complex impulse response (CIR), both in real time.

Various types of pilot carriers can be considered in the transmitted signal. The CFRs are extracted using channel estimation techniques using the known pilots. It is then possible to extract the main statistical parameters of the channel such as: power delay profile (PDP), path loss (PL), Doppler spectrum for a given delay, maximum delay, RMS (Root Mean Square) delay spread. The CIR or CFR data base will be then exploited to extract different types of channel models for example Tap Delay Line models or Geometrical channel models.

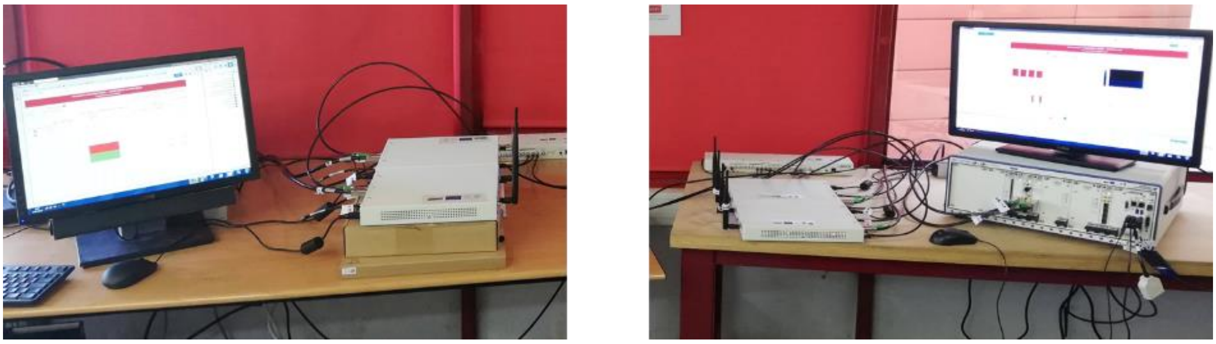

Figure 5.6: Sounding signal transmitter (left side) and receiver (right side)

Center frequency	10 MHz – 6 GHz
Bandwidth	20 MHz
Bandwidth used	18 MHz
Sampling rate	30.72 Ms/s
Number of pilots	1200
Subcarrier spacing	15 kHz
Frame structure	TDD
Number of symbols per frame	134
Cyclic prefix length	Normal (7symbols per slot)
Delay resolution / Min measurable delay	55.55 ns
Max delay	66.6 µs
Max output power	- 9 dBm
Max Doppler shift	7 kHz
Max theoretical speed	1260 km/h at 6 GHz
Continuous recording	1 hour
Antenna configuration	1x1 to 4x4

Table 5.1: Limitation of the SDR-based MIMO channel sounder

5.1.1.3.3 Measurement Constraints in the 5G-RACOM Project

To perform radio measurements, required for channel radio modelling task, the two channel sounders will be modified to be used in FRMCS frequency bands and to be adapted to the constraints. One of the first challenges is to perform measurements outside laboratory with trains. In fact, railway operational constraints will imply much more complexity and potential problems to solve than doing measurements with cars or vans.

In case of angle direction of arrival analysis, it is important to be able to measure accurately the phase of the incoming electromagnetic waves. Reference oscillator and channel sounder receiver are important, but it is not enough. Indeed, the length of cables between antennas and the channel sounder modifies amplitude and phase of the received signal. The best suitable configuration is to have low losses and paired RF cables (same phase and attenuation over the whole bandwidth). In any case, the characteristics of each cable must be known (complex transfer function and impedance).

The second important point is related to the antennas. They must be compliant with FRMCS band. For instance, shark antenna dedicated to Wi-Fi could not be used for this FRMCS measurement campaign. Several antennas on the train rooftop will be necessary. For 4x4 MIMO measurements at least four antennas are required. For direction of arrival estimate, specific geometry is required. Usually, Uniform Linear Array (ULA) is convenient for beamforming analysis. The distance between two adjacent antennas must be lower than 0.4 lambda (0.5 is not enough). Huber & Suhner antennas will be considered because they are compliant and dedicated to railway environment. For instance, the sencity® rail antenna (1399.17.012) support different cellular frequency bands. However, it is quite large (100 mm). This represent 1.5 lambda at 1900 MHz which is not compliant with ULA. As a result, other geometrical configuration has to be investigated to make direction of arrival estimate possible.

To conclude, the antenna array configuration on the rooftop of the train will be very important to have a successful radio measurement campaign.

5.1.1.4 Physical / deterministic channel models

Channel models for railway communications are different from those for traditional cellular and vehicle-to-everything (V2X) communications, which necessitates both new measurements and modelling approaches. Doppler effects due to high-speed and rapid transitions between different environments (cutting/tunnel, cutting/viaduct) make the HSL radio channels very specific compared to urban or suburban environments generally considered today in standardization groups (3GPP, 5GPP). Comprehensive reviews of HSL channel measurements and modelling are presented in [35], [34] and [48]. Narrowband measurements were mostly carried out in HSL scenarios considering the 930 MHz frequency in GSM-R systems [49], [50]. A single-input single output (SISO) antenna sounding system was generally used and the LoS propagation condition was usually measured in different railway environments, e.g., open space [51], hilly [52], cutting [49], viaduct [53], tunnel [54] and stations [55]. The transitions between environments are, in general, not considered. Regarding the train communication scenarios, the T2G propagation was largely addressed in the literature [55].

Based on the HSL measurements, the path loss (PL) was usually described as log-PL model and the large-scale fading was generally characterized with normal distribution in dB. In hilly terrain, a breakpoint distance in the estimated PLs was proposed, to consider the change in the dominant component: from LoS to scattered/diffracted paths. The impact of the height on the estimated PL was studied in viaduct environments [49]. It was found that the higher the BS antenna, the smaller the PL exponent and less fading severity. Various channel modelling approaches were proposed to characterize railway channels. However, geometry-based stochastic models are preferred for characterizing and emulating the 5G MIMO channel non-stationariness [48].

Ray-tracing (RT) is today recognized as a suitable solution to complement stochastic models and emulate spatially-consistent MIMO radio channel properties (e.g., the map-based approach in the 3GPP TR 138 901 model). Compared to the other deterministic channel models, RT has the advantage it can be implemented in a time-efficient manner; thus, it is compliant with large-scale and/or dynamic scenarios. Several works over the last ten years have demonstrated the interest and applicability of RT for railway scenarios. However, there are still many challenges to make RT suitable for infrastructure-to-train HST channel predictions at sub-6GHz frequencies. The 5G-RACOM project offers to enhance the RT model’s accuracy and scalability (i.e., applicable to most real-world situations).

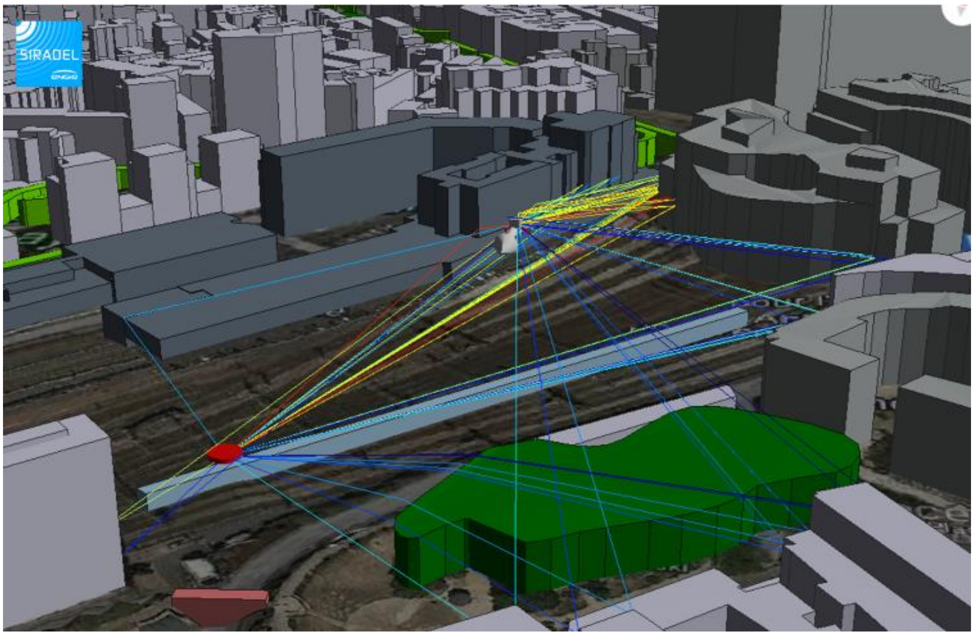

Figure 5.7: Ray-tracing applied on a railway scenario

In railway domain, a 3D RT technique is proposed in 2013 for train-to-infrastructure scenarios in HSL at 930 MHz [56]. The ray-tracing spatial consistency is highlighted in [57] based on the 3GPP HST scenario at 4 GHz. RT is also used to predict the train-to-infrastructure channel at high frequencies (5G millimeter-wave band or above) in [58] and [57]. Besides, the path-loss and Doppler spectrum are characterized in [59] from ray-tracing simulations at 3.5 and 30 GHz, based on the 3GPP R1-165484 urban, cutting and viaduct scenarios.

However, there are still key challenges to be solved so the RT tools can be conveniently utilized in sub-6GHz HSL studies: validation from channel measurements; consideration of dual-polar MIMO; scalability; and capability to jointly manage interactions at long-range and those from antenna nearby clutter. For that purpose, a prototype will be constructed from the Volcano RT edited by SIRADEL. Volcano RT applies for both radio channel emulation and radio-planning. The current solution covers rural environments, urban areas, indoors and tunnel scenarios, in sub-6GHz and millimeter-wave bands, by computing reflections, diffractions, attenuations and wall's diffuse scattering, providing polarized broadband MIMO channel estimates. The tool has not yet been qualified or tuned by comparison to channel sounder measurements in real HST scenarios; this will be done within the frame of 5G-RACOM. At the end of the project, we will be able to run train-to-infrastructure time-variant spatially-consistent MIMO channel predictions, with reasonable computation times. That will be demonstrated in several challenging scenarios, e.g., in urban areas or at the transition between two different environments, where long-range shadowing effects are combined with multiple interactions from buildings or clutter nearby the antennas.

Note the 3D digital model and the RT predictions will also be helpful for the identification and characterization of the main propagation paths observed by the channel sounder.

The literature survey proposed in [35] and updated within the project, shows that today there is a clear lack of large band dynamic MIMO channel modelling in railway environments at Railway frequency bands. We plan to fill this gap by characterizing and modelling railway radio channels thanks to the measurements collected in specific railway environments chosen with SNCF and FRMCS experts. The high-speed and environment impacts on the channel properties will be characterized and the non-stationarity aspect of the channel will be investigated, leading to tailored stochastic models. The physics of the multiple radio interactions will also be analysed and better understood to contribute to an enhanced ray-tracing, which applies to various real scenarios and environment transitions; combination with full-wave simulation techniques is thought as a key innovation to address the whole channel complexity.

5.1.2 Coexistence of FRMCS and GSM-R

Current GSM-R networks are deployed using FDD mode in a 900 MHz harmonized frequency band of 2 x 4 MHz (876-880 MHz uplink / 921-925 MHz downlink – R-GSM 900). If this spectral area is, in Europe, entirely devoted to the needs of GSM-R, some European countries have been authorized to take benefit from a spectral complement. This is particularly the case in Germany, Austria, Liechtenstein and Switzerland where the 873-876 MHz (uplink) and 918-921 MHz (downlink) frequency part may also be used for railways needs (ER-GSM Band). In 2020, CEPT has decided to conclude the harmonization of this 900 MHz frequency area allocating 2 x 5.6 MHz, (874.4-880 MHz uplink / 919.4-925 MHz downlink), always operated in FDD mode, for current and future railway needs. This band has been allocated at 3GPP (Q2 2022) as band N100, so called “RMR 900”.

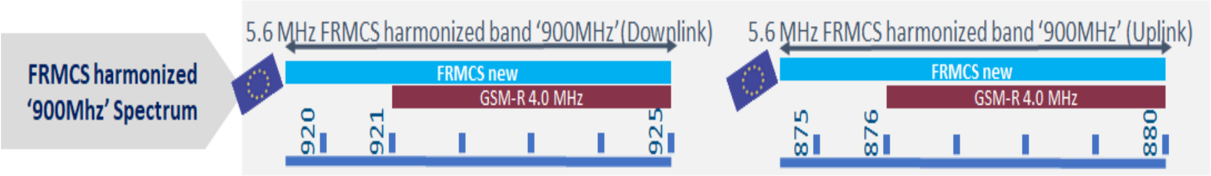

Figure 5.8: Harmonized FRMCS 900 MHz spectrum

This decision implies that the railway community has to address the coexistence issue between current GSM-R systems and the future FRMCS standard.

Moreover, in order to allow the introduction of new services that the future FRMCS system is supposed to offer, a need for additional spectrum has clearly been identified. Therefore, CEPT has decided to complement this native railway spectrum with an additional spectral band located in the 1900 MHz range introducing a block of 1 x 10 MHz (1900-1910 MHz) operated in TDD mode. This band has been allocated at 3GPP (Q2 2022) as band N101, so called “RMR 1900”.

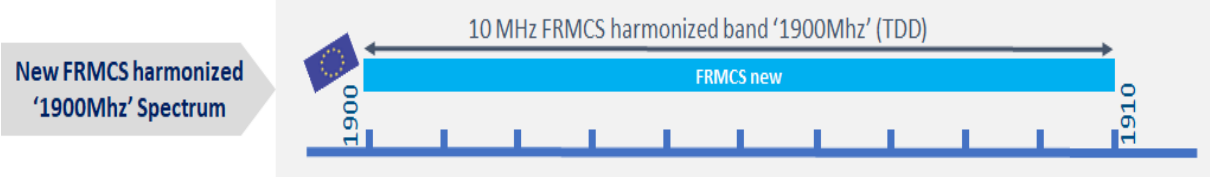

Figure 5.9: Harmonized FRMCS 1900 MHz spectrum

By this decision, the classical mono-layer GSM-R based railway system suddenly becomes a dual-layer system for which coexistence aspects in term of deployment and service management shall be carefully considered. The existing radio towers of the current GSM-R can be re-used for FRMCS in the 900 MHz and 1900 MHz frequency bands and additional radio tower shall be deployed to obtain, if needed, a continuous coverage for the 1900 MHz layer. If the average inter-site distance (ISD) is around 8 km in rural area for a 900 MHz deployment, it decreases to 4 km for the 1900 MHz band, while for urban cases the 900 MHz ISD of 4 km becomes something around 2 km for the 1900 MHz case. This further densification of radio sites for the future 1900 MHz FRMCS deployment implies a huge investment for railway operators. Moreover, with two frequency bands, the inter-band carrier aggregation principles as well as dual connectivity mechanisms shall be allowed in the 3GPP standard for these two specific railway bands. These mechanisms are more than useful to manage efficiently the throughput and capacity needs as well as mobility aspects.

To enable the coexistence between the GSM-R and the 5G FRMCS systems in the 900 MHz frequency band, a simple approach could be proposed. Considering the 2 x 5.6 MHz FDD part devoted to railway usage in the 900 MHz band, a GSM-R re-farming could be envisaged to release at least a bandwidth of 2 x 3 MHz, in uplink and downlink parts, on which a reduced 5G system could operate. As illustrated in the picture below, a narrowband 5G system is introduced adjacent to the GSM-R carriers that have been re-farmed.

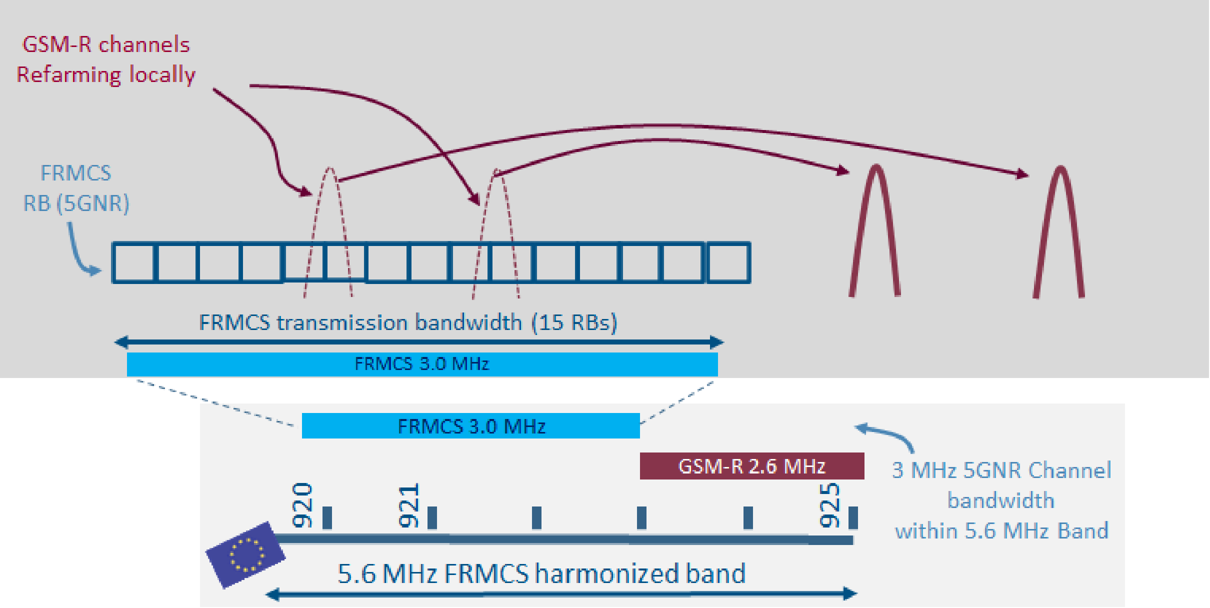

Figure 5.10: FRMCS GSM-R 900 MHz coexistence

With this approach, two problems arise. The first one is relative to the re-farming work that shall be done for the GSM-R being invited to migrate from a 2x4 MHz frequency part to a more reduced 2x2.6 MHz band. This work will force the railway operators to revisit globally their GSM-R network deployment. The second one is relative to the capability to deploy a 3.0 MHz system for FRMCS within the required timeframe based on availability of 3GPP standards.

A more innovative approach could consist of deploying a 2x5 MHz 5G-NR system overlapping the current 2x4 MHz GSM-R system. For that solution, two coexistence scenarios are currently under scope of the standardization. Both approaches are designed to operate in peacefully coexistence with the existing GSM-R system by minimizing inter-system interference. This is achieved through advanced scheduling techniques in the base station to protect GSM-R carriers while remaining fully compatible with standard 5G NR FRMCS handsets and cab radios (meaning no change on mobile devices required, standard RMR 900 UE used). In both, Whitespace and co-located approaches, the 5G resources will be limited.

5.1.2.1 Whitespace Approach

The “whitespace coexistence scheme” consists in locating onto the same frequency band, the current GSM-R technology and the 5G NR technology.

The main goal of this scheme is to allow a smooth introduction of the 5G NR RMR 900 inside the GSM-R band without impacting GSM-R performances. The aim is to not allocate additional spectrum nor introducing complex filtering solution to solve RF coexistence problems strongly impacting the legacy GSM-R system.

The proposed method ensures that in a given spectrum (on which GSM-R is already deployed) 5G NR deployment is possible with a maximized capacity not reachable by other methods.

The concept consists in reusing the inter GSM-R carriers frequency spaces as explained hereafter.

Considering the UIC frequency band, the concept is to place into the FRMCS band two railway systems: the current GSM-R 4 MHz standard and the future 5 MHz (25 RB's) OFDM 5G NR based FRMCS standard, for both UL & DL.

5G RB coinciding with GSM-R carriers are blanked in order to prevent GSM-R carriers from being disturbed by adjacent interferers. The resulting scheme, expressed as "Whitespace coexistence scheme" is depicted in the Figure 5.11.

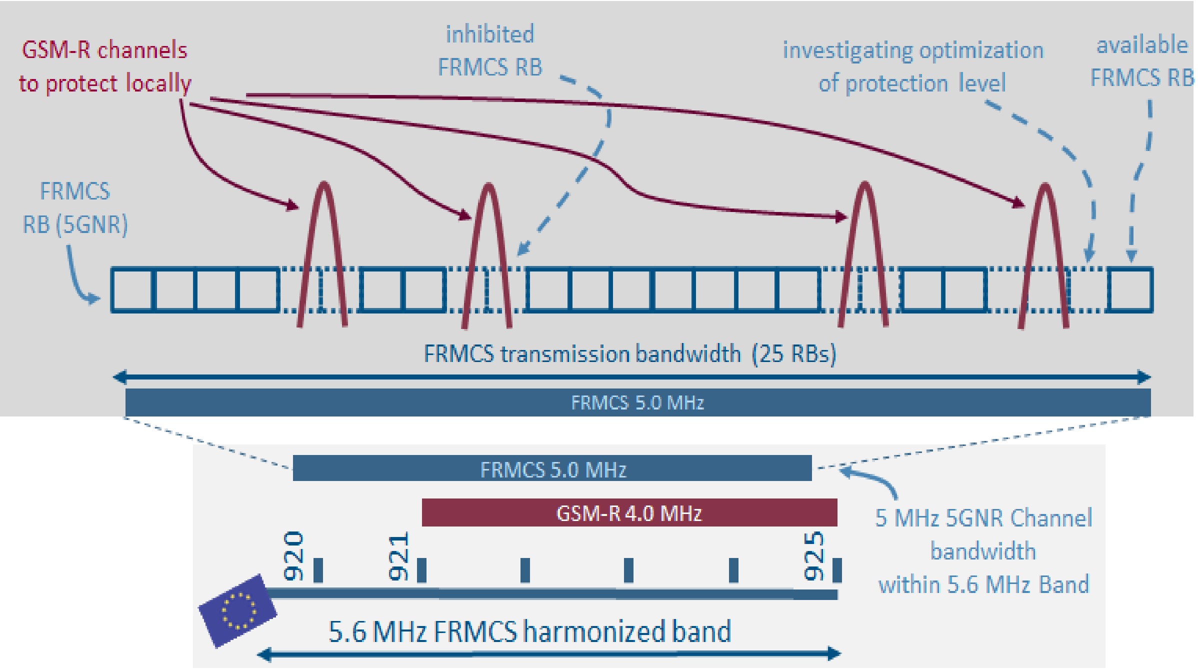

Figure 5.11: 5G NR & GSM-R UL/DL Co-location with blanked RB

In this context, two approaches will be investigated:

1. First (in the whitespace method), smart sensing will be proposed to detect the used GSM-R carriers and then inhibit 5G RBs that coincide with those carriers. In this case, cognitive-based radio scheduler will be proposed.
2. In the second approach (called co-located method), predictive and estimation models will be used to infer future network conditions (e.g., traffic volume estimation with temporal and spatial considerations, channel quality estimation, UE power head room (PHR) estimation, etc.). Accordingly, adaptive modulation and coding scheme (MCS) with variable transmit power based on Machine Learning techniques will be proposed to reduce interference with GSM-R carriers. In this case, one possible solution is to extend our previous work in [59], where we have proposed a DNN approach to predict the power headroom, for an enhanced Interference Mitigation and Traffic Adaptation (eIMTA) in 5G networks. Measurements and evaluation will be done using our 5G experimental prototype, based on Open Air Interface (OAI) [60].

Note that in both approaches, a coordination scheme between radio and computing schedulers in the context of 5G FRMCS is needed to satisfy application QoS requirements (in terms of throughput, processing time, packet loss, etc.).

5.1.2.2 Co-located Approach

Several design changes are necessary to facilitate the deployment of 5G NR in spectrum narrower than 5 MHz, but these changes should be minimized so that the established 5G NR ecosystem of devices and infrastructure can be efficiently leveraged without major changes in implementation. All of these changes will be made within 3GPP, thereby ensuring full interoperability between vendors and minimum guaranteed performance for RF and demodulation aspects. The current planned timeline for this work item in 3GPP is as follows: 3GPP RAN WG1 will work on it in the first half of 2023; RAN WG4 will continue the work in the second half. After that group will have finished, the specifications will be ready for the network side, however, RAN WG5 will need an additional 3-6 month period to work on the UE specifications. When RAN WG5 will have completed its work, the specifications will be ready for supplier implementations, which is expected for mid-2024 as part of 3GPP R18.

The co-located approach defines a reduced bandwidth for the 5G system as can be seen on the Figure 5.10, the NR carrier with bandwidth narrower than 5MHz is to be located at the lower end of the spectrum, while the higher end remains to be utilized by GSM-R carriers. This allows GSM-R to continue using at least part of its current spectrum portion. The gaps within the GSM-R block are intended to illustrate that not all GSM-R channels may be actively used in all of the deployments.

This approach is envisaged to support a block of up to 12 contiguous GSM-R carriers at the upper edge of the band, while providing at least 15 PRBs of contiguous spectrum for FRMCS at the lower edge of the band, or a block of up to 14 contiguous GSM-R carriers with at least 12 PRBs of contiguous FRMCS spectrum.

At the time of writing, work is ongoing in 3GPP RAN WG1/WG4 on this topic, and the accepted minimum FRMCS bandwidth depends on the outcome of the group's work. In both cases, GSM-R ARFCN 973 is assumed to be the highest channel number. The number of GSM-R carriers which can be supported will also depend on the required guard band width[1] between FRMCS and GSM-R. The operation of both GSM-R and FRMCS is fully independent from the other, thereby enabling multi-vendor deployments [61].

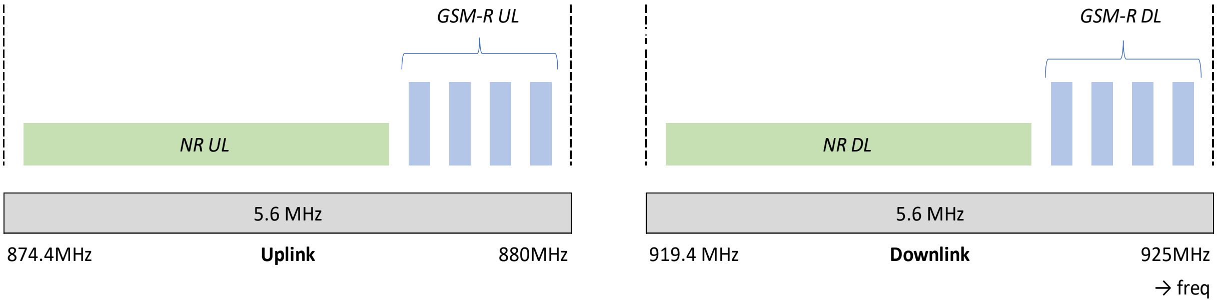

Figure 5.11: Planned frequency arrangement for the co-existence within N100

5.1.2.3 Lab Tests

The lab test shall discover different scenarios between GSM-R and 5G in general. Band N100 shall be used for testing. Aim is to explore possible protection mechanisms for professional radio which is operating in RMR in the band GSM-R | N100. To cover both, co-located and whitespace approaches, two generic setups will be proposed.

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[1] Note that the necessary guard band between FRMCS and GSM-R is assumed to be 200kHz but also is open for further study.

With the proposed co-located setup in the Figure 5.12, a) it shall be possible, to rate the influence of the 5G systems to the existing GSM-R. Uplink and downlink on the GSM-R has to be split to rate the impact on the uplink as well as on the downlink of the GSM-R UE. For the whitespace approach two 5G gNB generators are needed to create a gap in the band for operating the GSM-R. The Notch filter has to be tuned to the GSM-R channel, used for the measurements. An interesting aspect will be the measurement of the UE uplink path because the filtering mechanisms inside of GSM-R UEs are different.

For the co-located approach only one gNB generator is required to provide an interfering signal in the ER-GSM band while GSM-R UE is operating in the GSM-R band. Again, the influence on the UE uplink and downlink has to be rated separately.

There is additional difficulty for the measurement of the whitespace approach in a lab environment. Commercially available generators do not support the blanking out of resource blocks (RB) in N100. To simulate the number of suppressed RB's, there must be introduced notch filters as shown in the Figure 5.12, b).

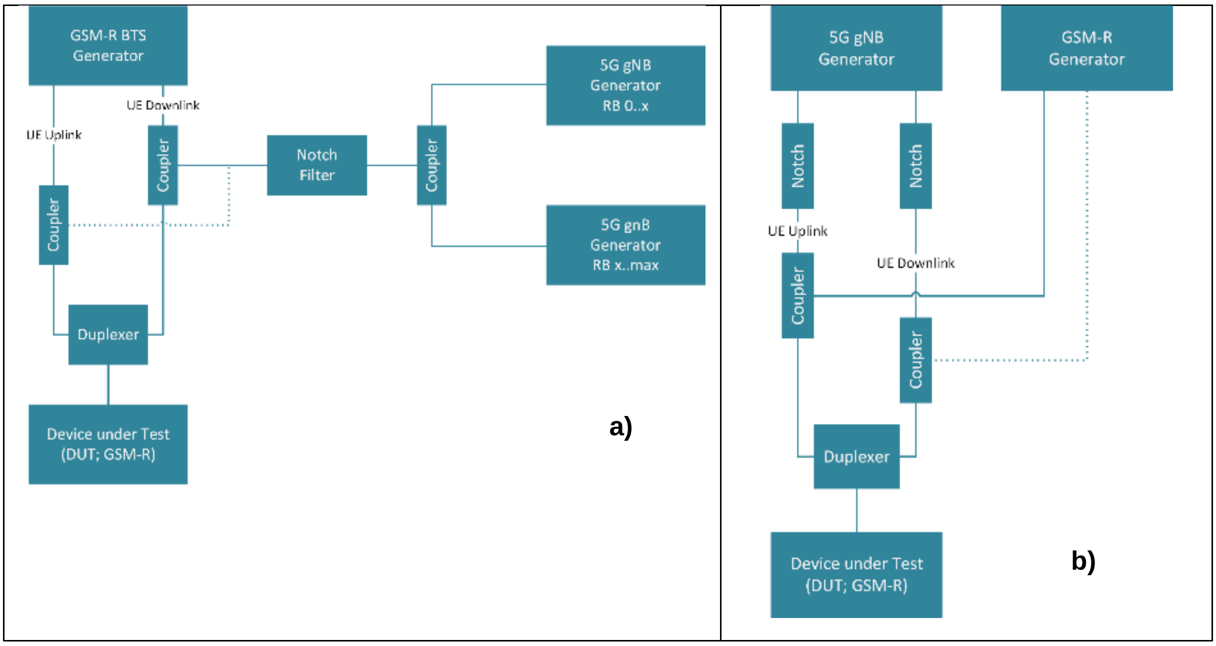

Figure 5.12: Setups for 5G impact on GSM-R; a) shows the general setup for 5G impacting the GSM-R UE in the co-located approach; b) provides the setup for GSM-R impacting 5G UE in the N100 band in the white space approach

The setup according to Figure 5.12, b) has a known handicap. According to a market analysis there is no test equipment available to support the blanking of special resource blocks inside a 5G signal. Only carrier aggregation is available as a method to combine separate carriers in a common 5G signal. So, the idea is, to blank out a set of resource blocks by notch out the narrow frequency band which is used for the GSM-R system. With the available notch filters in the RF lab it is possible to blank out a channel of minimum 200 kHz for the GSM-R carrier. According to an analysis of the 5G modulation schemes, the 5G system shall be able to detect the degraded channel conditions in the notched-out band. A reduction of the resource blocks for emulating the reduced bandwidth for the co-located approach is possible with the existing systems.

The test procedure must permit a direct comparison of the measured results obtained from both approaches.

KPI	Co-located	Whitespace
Data throughput on GSM-R for CSD connections	Next available GSM-R channel beside 5G signal with 12 RB 10 samples á 60 seconds	GSM-R channel in an RB gap of the 5G Signal
Data throughput on GSM-R for PSD connections		
Speech quality in		
Data throughput FRMCS	Maximum UL and DL rate in the 5G system with reduced number of RB	Maximum UL and DL rate in the 5G system without reduced number of RB
Interactions: does a transmission in GSM-R influence the data throughput in the 5G system and vice versa	Yes/no, ev. throughput reduction	Yes/no, ev. throughput reduction
Maximum output level of the 5G base station without influence on the GSM-R system	Tx Power and/or EIRP	
Maximum output level of the GSM-R base station without influence on the 5G system	Tx Power and/or EIRP	
Minimum value detection	GSM-R transmits with 8 W output power. Does it have influence to the 5G receiver in case of minimum receiving field strength	
Comparison of lab tests with tests in the live environment	Are the results comparable with the live environment	

Table 5.2: Basic KPI definition for comparable results

5.2 Hybrid FRMCS Networks

5.2.1 General Description

Hybrid FRMCS networks will combine a private 5G based FRMCS network with public 5G networks in order to provide seamless services for rail operation applications by increasing resiliency and availability, providing additional capacity and improving coverage. These benefits will be enabled by the use of additional and independent infrastructure of public 5G networks, access to additional frequency spectrum to offload bandwidth intensive applications, and the parallel use of multiple independent links that provide diverse connectivity transparent to the applications. The 5G-RACOM project will develop a hybrid FRMCS network architecture similar to the one defined in UIC FRMC SRS [62], ETSI TR 103 459 [28], as well as in the joint DB and Vodafone study [63] as “Architecture 2A: Dual Radio Scenario for Failsafe: Two onboard radios, with different SIM cards”, also shown in Figure 5.13 below. Following this architecture approach, the private FRMCS network and the public 5G network will not be integrated at 5G Core or RAN level but through a newly introduced “multipath function” (MPF). MPF will be located between 5G systems and MCX and will provide advanced transport protocols enabling multipath functionality needed in order to enable parallel and transparent use of several connections (paths). The public 5G network will be interfacing with the MPF as part of the FRMCS Trackside System.

The MPF included in this architecture is currently considered as a key function to support a hybrid FRMCS network approach. More detailed architecture for the integration of the hybrid FRMCS network approach will be defined within WP3 considering the overall architecture, requirements and capabilities of the private FRMCS network as well as the public 5G network at the Digital Rail Testbed (DTB) in the Ore mountains (Erzgebirge), Germany. It should be noted that operational FRMCS networks may be deployed using different architectures and should, in principle, allow further use cases like roaming, multiple transport networks, various access technologies and distributed architectures.

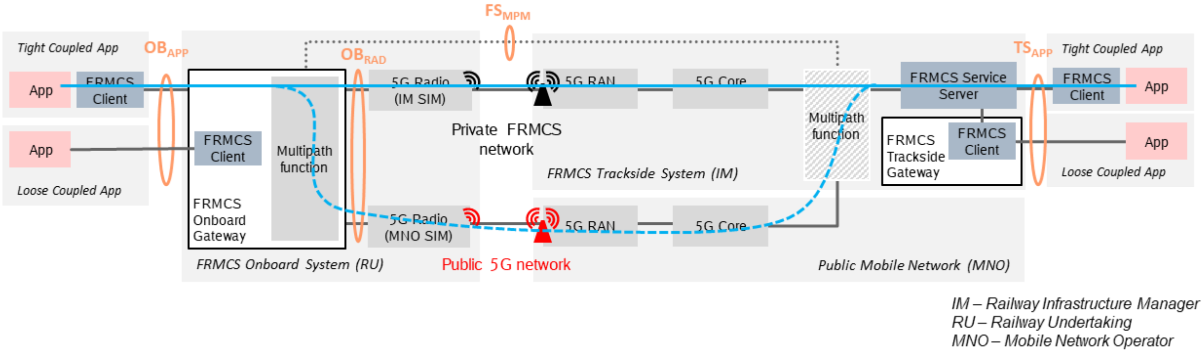

Figure 5.13: Hybrid FRMCS network architecture for 5G-RACOM with multiple network connections

Requirements on multipath functionality for rail operation applications (i.e., FRMCS multipath) are specified by UIC SRS [15]. By definition, FRMCS multipath is the capability that enables data connectivity using multiple transport paths over separate UEs, potentially supporting different radio access technologies (note: only 5G access technology is considered within the 5G-RACOM project) and shall make use of transport paths over one or multiple transport domains (e.g., private FRMCS and public 5G networks).

The multipath functionality, in general, is beneficial within a variety of scenarios and should support the following **high-level use cases**:

- Application specific path selection – selection of path (network) based on application type
- Resilience via fallback – switch path for selected (or all) applications if the network becomes temporarily unavailable or is degraded so that the required applications cannot be supported sufficiently
- Resilience via path selection – switch path for selected (individual or all) applications to increase the packet reliability of their associated traffic. This use case includes “Cell edge compensation”, i.e., RMR UE at front and rear end of the train, respectively.
- Resilience via duplication – transmit duplicated packets for selected (or all) applications via multiple paths to increase the packet reliability of its associated traffic
- Coverage complement – switch all applications if network coverage ends
- Capacity complement – traffic offload (switch/split) if the capacity is not sufficient
- Network transition – selecting a path/network for selected (or all) applications in situations where the network is changed, e.g., in border crossing scenarios (inbound/outbound)

Note that network transition via multipath is considered as a potential solution for border crossing in case requirements on service continuity cannot be fulfilled via a single UE. It should be noted that the above-mentioned use cases are referring to the envisioned capabilities of the general multipath function, while only a selection of it is supposed to be implemented at the DTB.

5.2.2 High-Level Functional Requirements

Based on the aforementioned use cases as well as the general FRMCS architecture and design paradigms, several **high-level functional requirements** can be derived for the multipath function (MPF), which are described in the following:

1. For **Session Specific Path Management**, requirements shall include functionality for path selection based on various criteria (e.g., priority, QoS, link quality, operator policies), specific per MCX session.

Routing operation policies (or rule sets) requirements are expected to govern the selection of one or more connections based on various criteria such as instantaneous quality of a transport domain (e.g., data rate, latency, error rate) and requested session attributes (e.g., required QoS parameters, application profile or data sensitivity). The policies are expected to be provided by the network side (railway infrastructure manager) and propagated via the multipath interface FS_MPM to the onboard side (see Figure 5.13).

2. Requirements shall include support of **Path Management Capabilities** (based on the multipath use cases) like path steering (best network selection), path switching (seamless handover) or other path management mechanisms (e.g., aggregation, duplication, providing also network aggregation capabilities). It shall allow reflection of demands of each individual rail operation application and can be based on static and dynamic routing capabilities.

3. From an **architectural** perspective, requirements shall include anchoring of the multipath related functions in the layered overall architecture for control plane and user plane, necessary reference points to support multipath functions (including potentially required internal reference points) in order to support the requested use cases.

   Based on the described mechanisms the multipath functions additional requirements are expected to separate the user plane and the control plane in a defined way. Currently the user plane is considered as the actual data transmitted via one or multiple paths (networks), the control plane comprises all the multipath signalling messages as well as the provisioning of the multipath policies, QoS information (potentially included in the policies) and real time monitoring data to assess the QoS fulfilment.

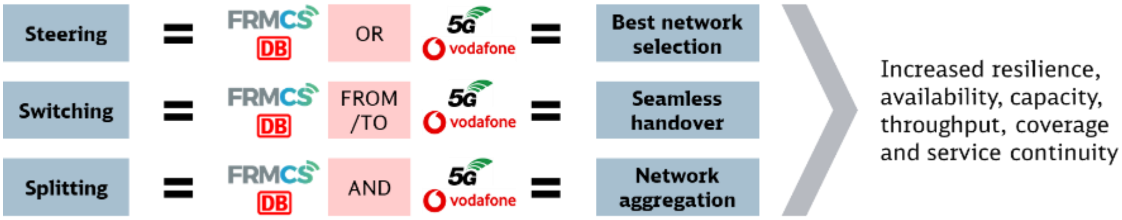

Figure 5.14: Steering, switching and splitting between connections provided by FRMCS and public 5G network as used by 5G-RACOM project

4. To ensure **Transparency/Decoupling** of layers, the requirements shall include transparency to MCX system, protocol independence for session protocols and as far as possible, and for avoiding impact on other network functionality (like framed routing, NAT, security, ...).

5. To ensure **Availability**, requirements shall include support of redundancy mechanisms for partial or full failure.

The project will analyse a **list of candidate multipath technologies** that include at least:

- MAMS (Multi-Access Management Services) [64],
- MP-QUIC [65],
- MP-TCP (Multipath –Transmission Control Protocol) [66],
- MP-UDP (Multipath – User Datagram Protocol),
- MP-DCCP (Multipath – Datagram Congestion Control Protocol) [67],
- SCTP (Stream Control Transmission Protocol) [68],
- ATSSS (Access Traffic Steering, Switching and Splitting) adjusted/extended for multiple networks,
- SD-WAN (Software Defined Wide Area Network) and

- Load Balancing based IP Routing.

One (potentially two, if agreed by the partners in WP3) multipath solutions/technologies will be selected for implementation, testing, measurement and demonstration at the DTB based on a detailed assessment plan. As part of the assessment, 5G-RACOM defines the following **high-level assessment criteria**:

- Fulfilment of the functional requirements
- Performance of multipath management (splitting, switching, etc) related to various criteria (e.g., packet delay, packet loss rate)
- Standardization and patents (in relation to vendor lock-in)
- Ongoing development
- Cost efficient deployment (due to technical considerations)
- Availability of Open-source implementation for OS platforms used to be relevant in railway developments (particular set to be agreed)

In this context, various multipath concepts and implementation architecture options need to be analysed, define routing operation policies criteria incl. control and enforcement mechanisms. Outcomes and proposal should be discussed with project external parties in the context of FRMCS standardization (incl. FRMCS equipment suppliers, 5G network infrastructure suppliers and other railways) as well as public mobile network operators in order to validate their potential availability in form of COTS/MOTS technologies and exposed interfaces.

5.2.3 Test Setup in the Digital Rail Testbed ”Digitales Testfeld Bahn (DTB)”

Implementation, testing and measurements foreseen to be undertaken in 5G-RACOM will be performed using the DTB. The implementation will be based on the generic hybrid network approach described above in this chapter and will be specified and further detailed within WP3.

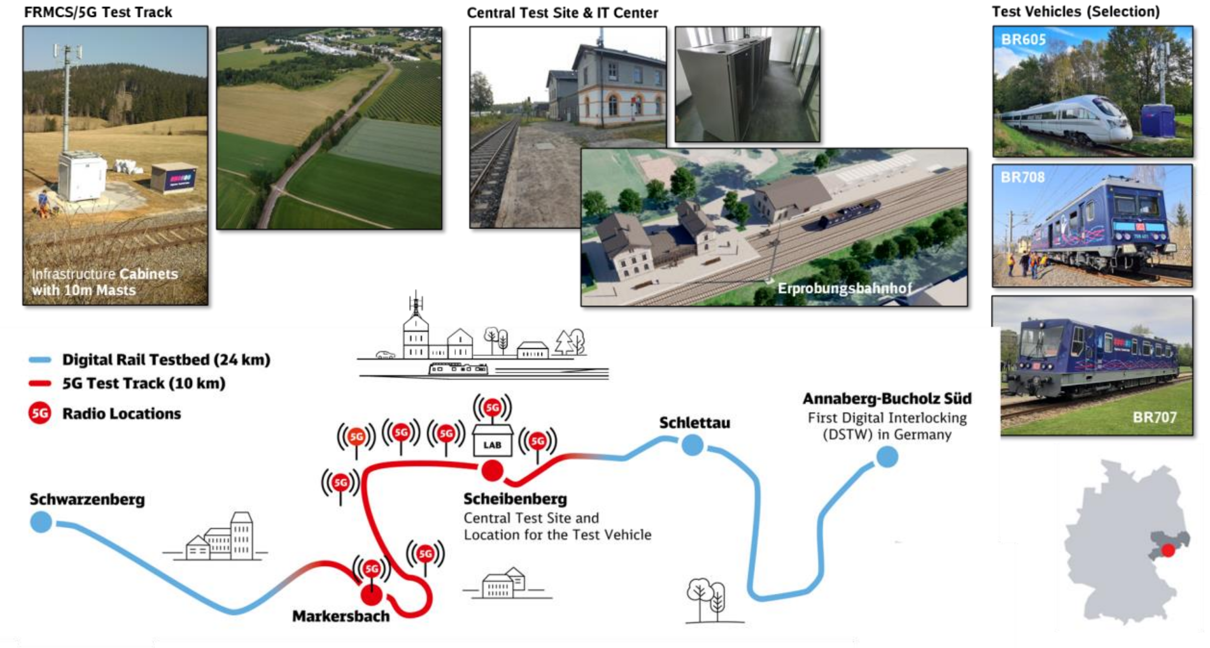

Figure 5.15: Overview of the Digital Rail Testbed “Digitales Testfeld Bahn (DTB)” at Erzgebirge, Germany

The testbed that will be used for 5G-RACOM WP3 is located between the towns of Schwarzenberg and Annaberg-Buchholz in a rural and moderately hilly area of the Erzgebirge region (ore mountains), Germany. The wireless networks cover an operational single-track line which can be used for experimentation and trials. The track is fully operational, however without regular/scheduled traffic, it allows a speed of 50-80 km/h.

The currently existing DTB setup consists of an FRMCS network, being operated by DB Netze along 10km of the 25km track, with 5G NR access (based on campus network frequencies in band N78) and 5G core for the transport stratum as well as MCX for the service stratum. This setup will be extended mainly with the multipath function on the trackside (activity of Kontron Transportation Germany) and potentially also with other 5G or service stratum functions. On the onboard side, the corresponding multipath function will be integrated based on the onboard setup by Funkwerk and Kontron. The FRMCS network with its data centre in Scheibenberg will be interconnected with a public 5G network provided by TU Chemnitz (having Vodafone subcontracted) with its data centre in Annaberg-Buchholz. Hence, the DTB multipath setup will provide a unique configuration consist of the private DB network interconnected with a public and the TU Chemnitz slice in a public cellular network operated by Vodafone.

An overview of the functional architecture with partner scoping is provided in the following diagram.

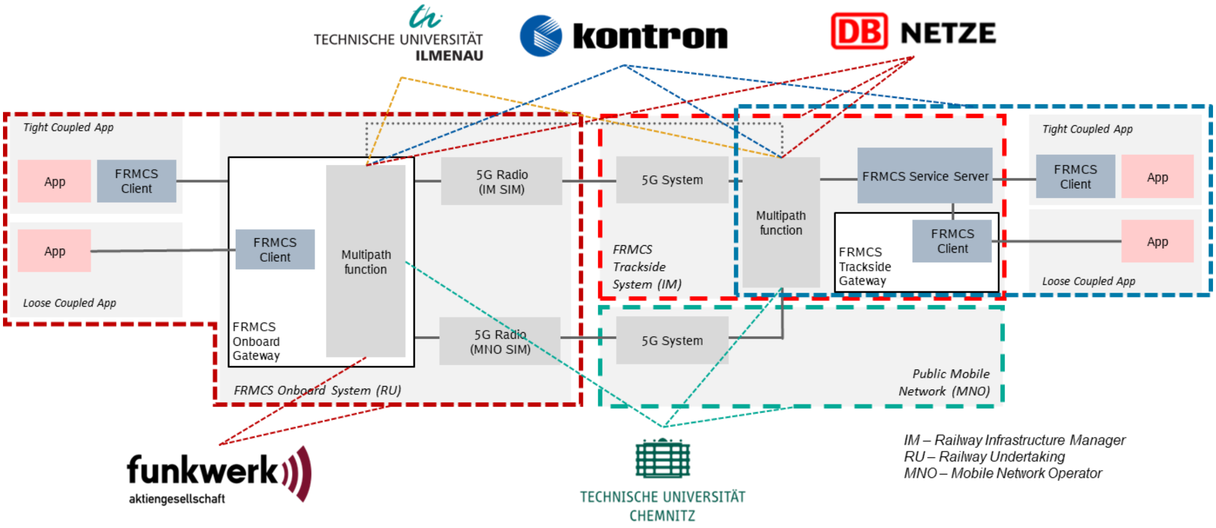

Figure 5.16: DTB Functional Architecture with Partner Scoping

The TU Chemnitz testbed is part of the Smart Rail Connectivity Campus (SRCC) in the Ore Mountains, this provides an experimental facility with 5G connectivity covering the 25km rail tracks as well as surrounding area. The Testbed facility (see figure above) has been established to investigate the role of 5G (and future cellular communication systems and wireless technologies) used as transport layer to facilitate the FRMCS (Future Rail Mobile Communication System). The ~25km are served completely (brown shaded) with 5G (SA) coverage in the 700MHz band, this part is operated by Vodafone and the TUC has their own slice and their own UPF in this public network covering this whole area along and beside the tracks. For 5G RACOM this slice on the public network will be used.

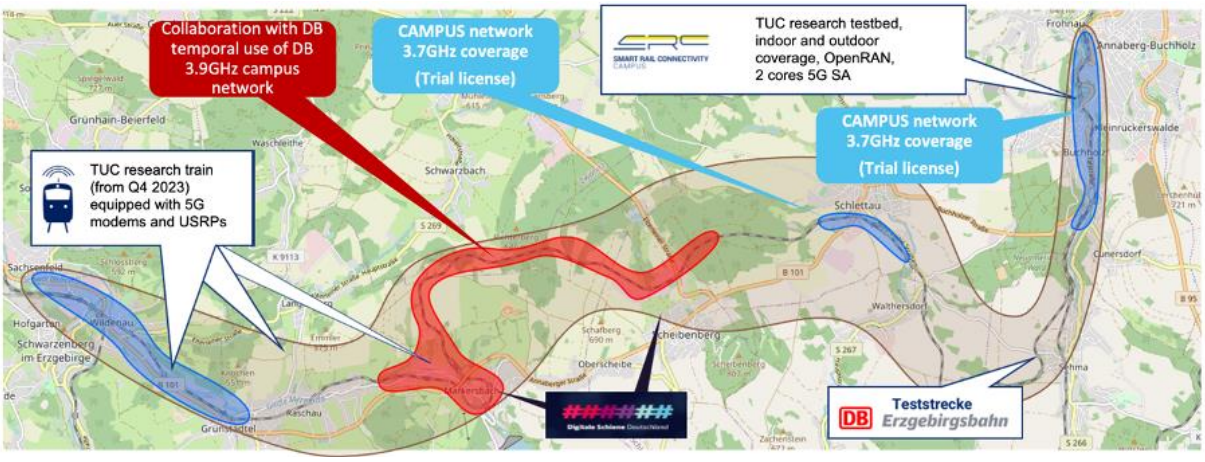

Figure 5.17: TUC-SRCC coverage area overlapping with the DTB Network

Beyond the public network coverage, there are two further Campus networks (shaded blue in the right half of the figure), that are run and operated by TUC, these are freely configurable campus networks covering the areas at 3.7GHz, here both outdoor and indoor coverage can be investigated. The campus network has two cores, a shared RAN and is completely reconfigurable depending on the use cases investigated.

6 Conclusions

This report introduces the project 5G-RACOM, it provides the motivation for FRMCS, the surrounding eco-system and standardization landscape and the topics subject to be analysed in the two legs of the project: Spectrum exploitation and spectrum extension. The relevant railway applications have been introduced together with assumptions on connectivity characteristics and QoS requirements, to give an understanding of the expected traffic mix in future rail operation systems. The basic architecture of FRMCS has also been introduced together with general assumptions, e.g., in relation to spectrum. In addition, the foundation for the two legs of the project is given with specific use cases, high-level requirements and general assumptions. The use cases, system assumptions and requirements, as well as the high-level architecture form the basis for further work in WPs 2 and 3.

7 Abbreviations

2G	2nd Generation of mobile communications aka GSM/EDGE
3GPP	3rd Generation Partnership Project
5G	5th Generation of mobile communications
5GC	5G core
ANFR	The national frequency agency
APS	Advanced Protection System
ARFCN	Absolute Radio Frequency Channel Number
ATO	Autonomous Train Operation
ATSSS	Access Traffic Steering, Switching and Splitting protocol
BMWK	Federal Ministry for Economic Affairs and Climate Action
BS	Base Station
CCS	Command, Control and Signalling
CEPT	Conférence Européenne des Administrations des Postes et des Télécommunications
CDL	Cluster Delay Line
CFR	Channel Frequency Response
CIR	Complex Impulse Response
CSD	Circuit Switched Data
CSS	Channel Sounder System
COTS	Commercial Off the Shelf
DB	Deutsche Bahn i.e., DB Netz AG
DL	Downlink
DNN	Deep Neural Networks
DTB	Digital Testfield Bahn or Digital Rail Testbed
E2E	End To End
EC	European Commission
eIMTA	enhanced Interference Mitigation and Traffic Adaptation
EIRP	Effective Isotropic Radiated Power
ERA	European Railway Agency
ERJU	Europe's Rail Joint Undertaking

ERTMS	European Rail Traffic Management System
ER-GSM	European Rail GSM band
ETCS	European Train Control System
ETSI	European Telecommunications Standards Institute
FDM	Frequency-Division Multiplexing
FRMCS	Future Railway Mobile Communication System
gNB	gNodeB i.e., BS in 5G
GoA	Grade of Automation
GPS	Global Positioning System
GSM-R	Global System for Mobile Communications – Rail
HSL	High Speed Line
HST	High Speed Train
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IM	Infrastructure Manager
ISD	Inter-Site Distance
KPI	Key Performance Indicator
L3	Layer no. 3 i.e., network layer in OSI reference model
LTE	Long Term Evolution aka 4G
LoS	Line of Sight
MA	Movement Authority
MAMS	Multi-Access Management Services
MCS	Modulation and Coding Scheme
MCX	Mission Critical Services
MEFR	Ministère de l’Economie et des Finances et de la Relance
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MOTS	Modified Off the Shelf
MP-DCCP	Multipath Datagram Congestion Control Protocol
MP-QUIC	Multipath Quick UDP Internet Connections protocol
MP-TCP	Multipath Transmission Control Protocol
MPF	Multipath Function

N3G	Non-3GPP Access
N78	3GPP 5G bands in 3500 MHz
NR	New Radio
N100/N101	3GPP 5G bands in 900/1900 MHz
OAI	Open Air Interface
OFDM	Orthogonal Frequency-Division Multiplexing
PDP	Power Delay Profile
PHR	Power Head Room
PL	Path Loss
PoC	Proof of Concept
PRB	Physical Resource Block
PSD	Packet Switched Data
QoS	Quality of Service
RACOM	Resilient and Green RAil COMmunications
RAN	Radio Access Network
RAT	Radio Access Type
RB	Resource Block
RBC	Radio Block Centre
REC	Railway Emergency Communication
RF	Radio Frequency
RFB	Railway Frequency Bands
RMR	Rail Mobile Radio
RMS	Root Mean Square
RT	Ray Tracing
RU	Railway Undertaking
SA	Standalone 5G network architecture
SD-WAN	Software Defined WAN
SDR	Software Define Radio
SISO	Single Input Single Output
SNCF	Société Nationale des Chemins de fer Français i.e., SNCF Réseau
SRS	System Requirements Specification
T2G	Train To Ground

T2T	Train To Train
TC RT	Technical Committee for Railway Telecommunications
TCMS	Train Control and Monitoring System
TDL	Tapped Delay Line
TDM	Time-Division Multiplexing
TSI	Technical Specification of Interoperability
TU	Technical University i.e., Chemnitz, Ilmenau
UE	User Equipment
UIC	International Union of Railways
UL	Uplink
ULA	Uniform Linear Array
USRP	Universal Software Radio Peripheral
V2X	Vehicle-To-Everything
WP	Work-Package

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